THE MEASUREMENT OF STEADY & FLUCTUATING TEMPERATURES

R. ROYDS

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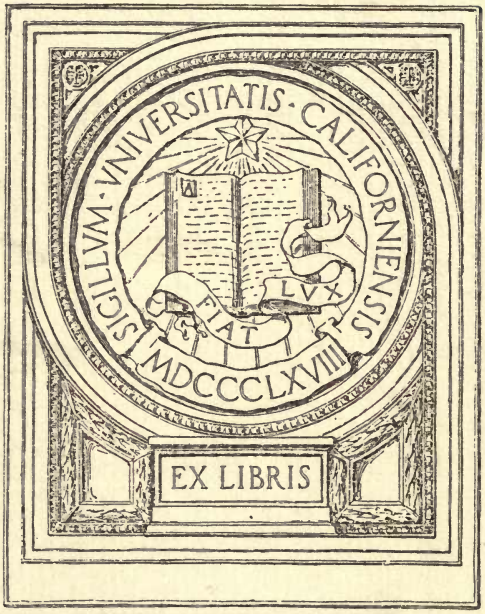

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THE MEASUREMENT OF STEADY AND FLUCTUATING TEMPERATURES

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BY

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PREFACE

THIS book is intended to give a concise account of modern methods of measuring both steady and fluctuating temperatures and to indicate their applications in industrial practice. Until recently the mercury thermometer provided the only important method of measuring temperatures in which most engineers could place any degree of confidence. But the need of some reliable means of measuring high temperatures beyond the range of ordinary thermometers led physicists to experiment with and to perfect other methods, in particular the thermo-couple and platinum resistance thermometers or pyrometers, and also radiation and optical pyrometers. In their hands these methods became so reliable under skilful operation that, with the increasing technical skill of engineers and metallurgists, their use has extended rapidly in industrial practice as a means of measuring or controlling the temperatures of gases, furnaces, solid and molten metals, etc. In some cases they have replaced the more or less haphazard method of guessing these temperatures by appearances, and their use in this direction is rapidly extending. In other cases, particularly in certain metallurgical operations, the temperatures need to be regulated so closely that a reliable means of measuring the temperatures makes all the difference between success and failure. Again, mercury thermometers are of little use in measuring the temperature of a thin metal wall or in following any rapidly fluctuating temperature with reasonable accuracy, and such measurements were only possible when the present methods became available.

The accurate measurement of temperature is also important in problems associated with the transmission of heat. In the author's works on *Heat Transmission by Radiation, Conduction, and Convection* and *Heat Transmission in Boilers, Condensers, and Evaporators*, the reader is sometimes referred

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to the present book for an account of the methods of measuring temperatures adopted or suitable for particular conditions of experiment concerning the transmission of heat. This present volume is therefore correlated with the above-mentioned works to that extent.

Acknowledgment is due to the Institution of Civil Engineers and the Institution of Mechanical Engineers for valuable information and illustrations from their *Proceedings*, and to the various firms mentioned in the text for particular data and for illustrations relating to their several products ; also to many other sources of information mentioned in the text, as well as to others too numerous to mention in detail.

ROBERT ROYDS.

DUNDEE, *September*, 1920.

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THE MEASUREMENT OF STEADY AND FLUCTUATING TEMPERATURES

CHAPTER I

THE MEASUREMENT OF TEMPERATURE

THE word temperature signifies the degree of hotness or the intensity of the heat in a body, measured according to some arbitrarily chosen scale. To measure temperature general use is made of various properties of materials, as, for instance, the expansion or contraction of bodies with changes of temperature, or the changes in the electrical properties of a body, or again, the radiation of a body may be utilised under special conditions.

The most suitable method for measuring temperature usually depends upon a multitude of circumstances, but it is evident that, whatever method is adopted, it is desirable to have a common scale of measurement, or at any rate, if more than one scale is used there should be a definite relationship between them. Experience has shown that the melting point of ice and the boiling point of water can be reproduced with great exactitude under definite conditions, and the ease with which pure water can be obtained has led to the range between these two points being adopted as the Fundamental Interval to which all measurements of temperature are referred.

The "freezing point," as the lower fixed point is called, is usually determined by placing the instrument or "thermometer" in a vessel surrounded by finely broken pure ice from which the water is dripping. The boiling point is determined by placing the thermometer in the saturated steam

coming from boiling water with the pressure at one standard atmosphere, i.e. 760 mm. vertical column of mercury in the latitude of Paris, equivalent to 29·905 inches in the latitude of London.

The most common scale of measurement used by English-speaking engineers is the Fahrenheit scale, where the freezing point is called 32 degrees (32° F.) and the boiling point 212 degrees (212° F.). Thus the range from the freezing to the boiling point is 180°.

The Centigrade scale is sometimes used by English-speaking engineers, but more generally by physicists and chemists, and also by engineers on the Continent of Europe. The freezing point is called 0 degrees (0° C.) and the boiling point 100 degrees (100° C.). Thus a change of temperature of 1° F. is equivalent to a change of $\frac{100}{180}=\frac{5}{9}$° on the Centigrade scale.

Thus, temperature in degrees Cent.$=$(deg. Fahr.$-32)\times\frac{100}{180}$. An easily remembered rule to convert from deg. Fahr. to deg. Cent., or *vice versa*, is to add 40 to the temperature reading, multiply by $\frac{5}{9}$ or by $\frac{9}{5}$ as the case may be, and then subtract 40.

For practical use a thermometer needs to be graduated in degrees of temperature, and whatever may be the type of thermometer subjected to any particular temperature the reading should be definite and invariable if true temperatures are to be recorded. It is known, for instance, that although a mercury thermometer usually has the degree divisions equally spaced along the stem, mercury does not expand at quite a uniform rate with increase of temperature. Most other substances have similar defects and involve similar discrepancies. Thus, even though the freezing and boiling points might be correctly recorded by different types of thermometers, it does not follow that the intermediate readings would necessarily agree, and it becomes necessary therefore to have some definite standard of comparison.

The zero points on the ordinary scales of temperature referred to previously were originally fixed upon because of their general convenience and without considering their relationship to what is called " the absolute zero " of temperature. The absolute zero refers to that temperature at which there would be no heat in a body, and although the absolute

zero of temperature has never been reached, its value in relation to the ordinary scales of temperature has been accurately determined by indirect means.

Standard Thermodynamic Scale of Temperature.—The necessity for some standard scale led Lord Kelvin in 1848 to propose the thermodynamic scale, based upon the Carnot cycle* for heat engines. On this theoretical cycle a quantity of heat Q_1 is supposed to be taken in by the working substance at the absolute temperature τ_1, and the quantity of heat Q_2 rejected at the absolute temperature τ_2. It can be shown that, no matter what the working substance may be,

$$\frac{Q_1}{Q_2} = \frac{\tau_1}{\tau_2}$$

$$\text{or, } \frac{Q_1}{\tau_1} = \frac{Q_2}{\tau_2} \quad \ldots\ldots\ldots\ldots (1)$$

it will be noted that if Q_2 were zero the value of τ_2 would also be zero, that is, the "absolute zero of temperature."

It can also be shown that if a Carnot cycle engine works between the temperature limits, say, 100° C. and 0° C., then for every 373 units of heat put in at 100° C. it will turn 100 units into work and reject 273 units at 0° C. The ratio of these temperatures on the thermodynamic scale is therefore 373 : 273, and thus the freezing point would be 273 degrees on this scale.

Experience has shown that it is practically impossible to carry out the Carnot cycle completely, and thus, while the idea is a useful conception, no practical thermometer can be constructed to use the Carnot cycle directly. It can be proved, however, that an equivalent measure of temperature is given by the expansion of a perfect gas with increase of temperature,† and as there are the gases, hydrogen, nitrogen, oxygen, etc., which nearly obey the laws of perfect gases, such can be used to give a standard measure of absolute temperature. The characteristic equation expressing the fundamental law of a perfect gas is

$$PV = R\tau, \quad \ldots\ldots\ldots\ldots (2)$$

* For a detailed description of this cycle, reference may be made to any standard textbook on "Heat" or "Heat Engines."

† See Preston's *Theory of Heat*, p. 716, 1904 edition.

where, P=absolute pressure; V=absolute volume; τ= absolute temperature, and R is a constant depending only upon the mass of gas under consideration.

Thus if P_1, V_1, τ_1 represent the pressure, volume, and temperature of a certain mass of perfect gas under one condition, and P_2, V_2, τ_2 represent the above relations of the same mass of perfect gas under other conditions, then,

$$\frac{P_1 V_1}{\tau_1} = \frac{P_2 V_2}{\tau_2} = R.$$

$$\text{If } V_1 = V_2, \text{ then, } P_1 - P_2 = \frac{R}{V_1}(\tau_1 - \tau_2) \quad . \quad . \quad . \quad (3)$$

i.e. if the volume is kept constant the change of pressure is a measure of the change of temperature.

Again, should the pressure be kept constant at value P_1, then,

$$V_1 - V_2 = \frac{R}{P_1}(\tau_1 - \tau_2) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

i.e. at constant pressure the change of volume is a measure of the change of temperature.

Regnault found that the constant volume gas thermometer was more accurate in practice than one at constant pressure. Fig. 1 shows in outline the apparatus adopted in his experiments. The bulb A was filled with pure dry air at a pressure of 760 millimetres of mercury and was connected to the manometer tube BC. When the temperature of the bulb A increased the mercury in the leg B was kept at a constant level O by pouring mercury into the leg C. The difference of level h is a measure of the increase in the temperature of the bulb A from some standard condition. The thermometer would be calibrated by immersion in ice for 0° C. and in steam at normal atmospheric pressure for 100° C.

According to Regnault, if P_{100} is the absolute pressure of the air in the bulb at 100° C. and P_0 that at 0° C., then for air,

$$P_{100} = 1{\cdot}3665\ P_0 \quad \text{(volume constant)},$$

$$\therefore \text{ from eqn. 3, } P_0 \times {\cdot}3665 = 100\frac{R}{V_0}$$

$$\text{or, } \frac{V_0}{R} = \frac{272{\cdot}85}{P_0}$$

Thus any temperature t° C on this scale would be given by

$$t = \tau - \tau_0 = \frac{V_0}{R}(P - P_0)$$

$$= 272{\cdot}85\left(\frac{P}{P_0} - 1\right)$$

If $\tau = 0$, then $P = 0$ and $t = -\tau_0 = -272{\cdot}85°$ C., and this therefore represents the absolute zero of temperature on this scale. Dry air, however, does not quite follow the laws of a perfect gas between 0° C. and 100° C., but hydrogen has been found to behave very nearly as a perfect gas between these temperatures.

Calculations based upon the physical properties of hydrogen gas show that the corrections necessary to bring the hydrogen gas thermometer into agreement with the thermodynamic scale are no greater than the experimental errors involved in gas thermometry. In order, therefore, to fix a definite practical standard the International Committee of Weights and Measures have adopted the *hydrogen* thermometer, the bulb being filled with the pure gas at an absolute pressure of 1000 mm. of mercury at the temperature of melting ice, the thermometer to be used at constant volume. According to the calculations of Professor Callendar* the corrections to be made to bring the hydrogen scale into unison with the thermodynamic scale are not greater than about +·044° C. at 1000° C. and are much less than this from −100° C. to 500° C. The absolute zero of temperature is found to be very near the value −273° C. (−460° F. nearly).

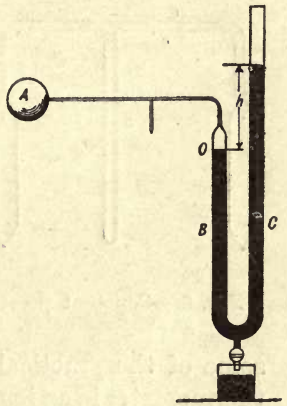


FIG. 1.—Constant volume gas thermometer.

The hydrogen thermometer can be used up to about 500° C. or so, but if the temperature is much above this the hydrogen passes through the iridio-platinum bulb. Porcelain is gas-tight to over 1000° C. if glazed, but the glaze begins to melt

* *Phil. Mag.*, January, 1903.

at about 1100° C. Also at high temperatures hydrogen has some slight action on porcelain. Glass, of course, is fusible at high temperatures. On account of these difficulties nitrogen is more often employed in gas thermometry for high temperatures, using preferably an iridio-platinum bulb. Messrs. Holborn and Day have used such a thermometer up to 1300° C. (2372° F.). The corrections for nitrogen in reducing the readings to the thermodynamic scale are rather larger than for hydrogen, being, according to Professor Callendar,* +0·65° C. at 1000° C.

For accurate measurements certain small allowances are necessary on account of the expansion of the bulb and the change in the temperature of the gas in the tube connection between the bulb and the manometer. With the constant pressure (variable volume) thermometer an additional correction is necessary due to the varying volume of the dead space, besides which the "thermodynamic scale correction" is rather larger than for the constant volume (pressure variable) thermometer. Professor Callendar has overcome some of the practical difficulties of the constant pressure gas thermometer in an ingenious manner. Referring to the diagrammatic representation of his apparatus in Fig. 2, the bulb T containing air is subjected to the temperature to be measured and is connected up to the mercury bulb M by a suitable length of tube E. I is a similar bulb filled with air and is immersed in melting ice, and the manometer tube S, partly filled with sulphuric acid, connects the two tubes E and F. By making the tube F of similar form to the tube E and placed in the same position so that both acquire the same temperature conditions, the dead space in tube E is compensated for by that in tube F, and thus no tube corrections are necessary. When the temperature of the bulb T is altered the amount of mercury in the vessel M is adjusted until the sulphuric acid in the

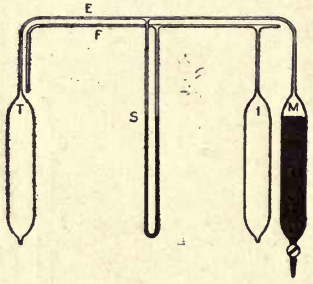


FIG. 2.—Constant pressure gas thermometer.

* *Phil. Mag.*, January, 1903.

manometer S stands at the same level in the two legs and then it is known that the pressure in T is the same as that in I. Since the bulb I is kept at a constant temperature and volume it follows that the pressure will be constant. The change in the volume of air in the bulb M is a measure of the change of temperature.

From the engineers' point of view, however, the gas thermometer is not at all convenient for ordinary measurements of temperature, and it can only be considered as the standard for reference purposes. The method of measurement used in practice depends to a large extent upon circumstances, such as, for instance, the temperature to be measured, the degree of accuracy required, whether the temperature is "steady" or "variable,"* and the general convenience of the method adopted for the particular purpose. For example, the mercury thermometer is well suited for the measurement of ordinary temperatures of a steady character, but owing to time lag it is not of much use in determining instantaneous values of rapidly varying temperatures, such as occur at the inside surface of a steam engine or a gas engine cylinder. Neither is the mercury thermometer of much use where the space available for its insertion is very limited, as, for instance, if required to measure the temperature of a condenser tube having a thickness of, say, ·049 in. (18 B.W.G.).

* "Steady" in the sense that any variations are small and take place very slowly; "variable" may be taken to mean variations which occur in a comparatively rapid manner.

CHAPTER II

MERCURY THERMOMETERS

The expansion of a suitable liquid is commonly used to indicate temperature. Mercury in glass is most generally suitable on account of its fairly regular expansion with increase of temperature, and it can be used over a comparatively large range, the freezing point of mercury being about −39° C. and its boiling point at normal atmospheric pressure 358·5° C. (about 677° F.). Its low specific heat and high conductivity also enables it to acquire readily the temperature of the surroundings. Such liquids as alcohol, ether, etc., possess a larger coefficient of expansion, a higher specific heat, and a lower specific gravity than mercury, but they are not generally suitable for the measurement of temperatures commonly dealt with by engineers because of the comparatively low boiling points of these liquids.

Although an engineer would hardly ever be called upon to construct a mercury thermometer, a brief description of the methods in use may assist one to realise some of the difficulties attending the accurate measurement of temperature. In making a mercury thermometer a capillary tube of uniform bore would have a bulb of suitable size blown at one end. The uniformity of the bore could be tested by drawing in a short thread of mercury to different positions in the tube, and if this thread were found practically of uniform length at the various positions in the tube it would follow that the bore was approximately uniform. If appreciable differences of length occurred the tube would be rejected. The tube and bulb would be cleaned in boiling nitric acid to remove all organic matter. The empty bulb would sometime afterwards be heated to expel some of the contained air and the open end

of the tube then dipped under the surface of the mercury so that, as the bulb cools, some mercury is forced into the tube and bulb. To fill completely the bulb the mercury thus introduced is heated and boiled to expel all the air, the bulb and tube being then filled with mercury and its vapour. Dipping the end below the surface of the mercury and allowing the bulb to cool the mercury then enters the tube as the vapour condenses and completely fills the instrument. Some difficulty is usually experienced in getting rid of all the air, as minute bubbles are liable to attach themselves to the sides of the glass and are difficult to dislodge. Any air left would not only be likely to affect the accuracy of the thermometer, but would be liable to cause a separation of the column of mercury, particularly if measuring fairly high temperatures. When the bulb and tube or stem are filled completely the instrument is raised to the region of the highest temperature to be measured and the end hermetically sealed while in this state. To obviate the bursting of the thermometer should it be accidentally raised afterwards to a temperature beyond its range, it is usual to have the upper end of the tube widened out before sealing, and this in practice is often found to be a necessary precaution. If the size of the bulb and stem have been suitably arranged the bulb and the lower part of the stem would be filled with mercury at the lowest temperature intended to be measured.

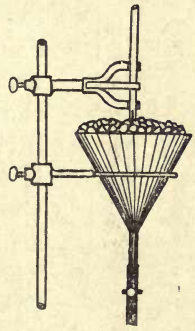


FIG. 3.—Determination of freezing point.

For actual use, of course, it is necessary to mark a scale on the stem of the thermometer and it is usual to mark the two fundamental points, i.e. freezing and boiling points, before graduating the stem. A common arrangement for the determination of the freezing point is shown in Fig. 3. The thermometer is supported as shown with the bulb and part of the stem surrounded with finely broken pure ice* and having the thread of mercury just exposed to view. The melted ice is

* Ordinary commercial ice manufactured from clean water is usually sufficient for the purpose when well washed.

allowed to drip slowly from the funnel. If impure ice only is available the thermometer might be placed in a test tube containing pure water and the test tube surrounded with the ice. In this case the water would begin to freeze and would eventually arrive at the freezing point. In due course the reading of the thermometer would become constant and this position would be marked on the stem as the freezing point.

The boiling point is determined by placing the bulb and column of mercury in contact with steam at the standard atmospheric pressure.* A suitable apparatus is represented in Fig. 4 and is self-explanatory. The thermometer is placed as shown clear of the boiling water so that the top of the column of mercury is just exposed to view, and when the reading becomes constant the stem is marked provisionally, but this would only correspond to 100° C. (212° F.) provided the pressure was at the standard value. This involves the correct reading of the barometer, and if the absolute pressure of the steam differs from the standard an allowance has to be made in accordance with the values given in Table 1, p. 157. The correct position on the stem is then marked. It is desirable, of course, to choose the boiling point determination when the barometer is steady. When aiming at the highest degree of accuracy, barometer corrections may be made to allow for latitude, altitude above sea level, and the temperature of the mercury in the barometer. It is usual to divide the stem between the freezing and boiling points into equal divisions.

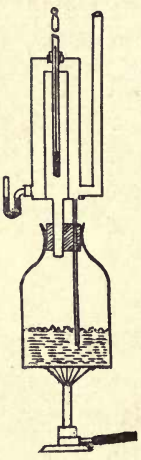


FIG. 4.—Determination of boiling point.

Errors of Mercury Thermometers.—It was mentioned on p. 5 that the hydrogen thermometer has been adopted as the standard of reference. Mercury thermometers, when compared with this standard, are liable to certain inaccuracies, the importance of which depends to some extent upon the degree of accuracy required in using the thermometer. Generally speaking, engineers in practice do not require the same degree of accuracy in measuring temperatures as the

* See p. 2 for definition.

physicist or chemist working in the laboratory, mainly for the reason that in ordinary experimental work the engineer usually has to put up with, or is subject to, large instrumental errors in other directions, as for instance, in the ordinary steam or gas engine indicators. Also the engineer generally has to work on plant of comparatively large dimensions and it is often a difficult matter to measure true temperatures, quite independent of possible thermometer errors, as, for example, in measuring the temperature of flue gases in a large flue. Notwithstanding such limitations, however, occasions arise when temperature measurements of a high degree of accuracy are essential.

Thermometer errors may be divided into two classes: (1) Personal errors of observation, and (2) Instrumental errors. With regard to errors of observation, when a reading is taken care should be exercised to avoid parallax, that is, the line of sight should be perpendicular to the stem of the thermometer. Careful watch should also be kept to see that no part of the thread of mercury has become detached from the main column. Any detached portion can generally be got back by jerking the thermometer while holding it in the vertical position, or if this is not successful, by heating the thermometer to a sufficiently high temperature so that the main column joins the detached portion. Should it be found that the detached portion moves upwards before the main column reaches it and the two do not join properly, this generally indicates the presence of an air bubble, and for accurate work the thermometer should be rejected as useless; even for ordinary work little confidence could be placed on its readings. For instance, in a particular case when using an ordinary mercury thermometer, the indications were suspected by the writer of being several degrees too high. On testing the thermometer at the boiling point the reading came out to be about 10° F. too high and on careful inspection it was seen that a very small bubble was lodging at the mouth of the bulb. After cooling to below this point and re-testing, the thermometer was nearly correct; but no confidence could ever be placed in its use afterwards.

With respect to instrumental errors, besides that just

mentioned there is the possibility of errors due to—(1) Defects of the glass bulb. (2) Internal pressure. (3) External pressure. (4) Time lag. (5) Differences between mercury and hydrogen scales. (6) Exposure of stem, and (7) Defects in the thermal contact with the body whose temperature is measured. It is well known that glass, when heated and allowed to cool to the original temperature, does not immediately return to its original volume. This effect may be observed in a mercury thermometer by placing it in melting ice and after it has attained a steady reading taking it out and subjecting it to the boiling point temperature for thirty minutes or so. Then on returning the thermometer to the ice it would be found that the reading with an ordinary thermometer was perhaps 0·5° F. lower than previously. In the course of days, or perhaps weeks, it would probably return to the original reading. This change of reading just referred to is sometimes called the " depression of zero," and it is found to increase the higher the temperature to which the thermometer has been subjected.

Great attention has been paid on the Continent to the manufacture of glass most suitable for thermometers. The Bureau International has devoted attention to the French *verre dur*, and the Reichsanstalt to certain Jena glasses ; particularly those known as 16^{III} and 59^{III} have been examined in detail. It is found that with these glasses the depression of zero can be allowed for in a reliable manner by taking a reading in ice, that is, the freezing point, immediately after the higher temperature has been obtained. With this object in view it is usual to determine the fundamental interval by taking the boiling point first and immediately after this the freezing point, intending the thermometer to be used in this manner. This procedure is necessary when a high degree of accuracy is required, but to take an ice reading in order to get the true freezing point immediately after any observation of a higher temperature is very troublesome in practice, and with high temperatures there is some risk of breaking the thermometer. In ordinary practice, therefore, it is not usual to go through the above procedure in measuring temperatures by mercury thermometers.

After manufacture the glass bulb of a thermometer is also liable to a decrease of volume in course of time, particularly if heated frequently to high temperatures, and this would cause a serious rise of the zero and of other readings unless the thermometer was well made. This effect, however, is almost eliminated by the best makers by subjecting the bulb to prolonged annealing after manufacture. Thorough annealing requires from four to ten days at about 840° F., and followed by a period of slow cooling for from three to six days.* The total change of the ice point for this process of annealing is about 30° C. (54° F.) for Jena 16^{III} glass, and from 20° C. to 30° C. (36° F. to 54° F.) for Jena 59^{III} glass. Hence the importance of thoroughly annealing and ageing the glass bulb before filling with mercury. For the best work the bulb would be laid aside for several months to age the glass, because it is found that slow changes of volume occur for a long period after annealing.

Errors due to variation of internal pressure on account of the head of mercury may cause slight errors in very delicate thermometers. The Bureau International and the Reichsanstalt calibrate thermometers in the horizontal position, and when a delicate thermometer is afterwards used in a vertical position the head of mercury may slightly alter the volume of the bulb and thereby affect the reading slightly. This error can be allowed for, but is usually of no particular importance in ordinary thermometers.

The influence on the volume of the bulb of variations of external pressure due to alterations of the pressure of the atmosphere are not of any importance except in very delicate thermometers. In any case a thermometer bulb should not be subjected to a pressure much different from that obtaining during calibration, or if it is unavoidable a correction, if necessary, should be adopted by noting the change of the mercury column due to the pressure on the bulb and making an allowance accordingly.

Errors due to the lag of a thermometer in taking up the temperature to which it is subjected is only of importance

* *Heat Treatment of High Temperature Mercurial Thermometers,* by Dickinson, U.S.A. Bureau of Standards. Reprint No. 32.

when a varying temperature is being measured. When necessary it can be allowed for approximately when the change of temperature is quite slow by plunging the thermometer into a region of constant temperature and noting the readings at definite intervals of time. In any case a mercury thermometer would not be able to record rapidly fluctuating temperatures, such as occur, for instance, at the working face of a steam engine cylinder.

Between the freezing and boiling points it is ordinarily intended that equal changes of volume of the mercury should signify equal changes of temperature. If the capillary tube forming the stem is of uniform bore this would correspond to equal divisions on the stem. Slight inequalities in the bore generally exist and this can be tested approximately by detaching a short portion of the thread of mercury and measuring its length at different positions. A convenient length of the thread can usually be detached by jerking the thermometer when up-ended. If the divisions on the scale are of equal length, which is usually the case with French or German thermometers, approximate corrections for temperature can be readily made for any inequalities of the bore in the manner just indicated.

Owing to the fact that the relative expansion of mercury and glass does not take place at quite a uniform rate with changes of temperature as measured on the hydrogen scale, for accurate work it is necessary to compare a mercury thermometer with the hydrogen thermometer. With all the ordinary kinds of glass the divergence seems to be greatest in the neighbourhood of 40° C. (104° F.) and is of the order of $\frac{1}{10}$° C., say, about $\frac{1}{5}$° F., the mercury thermometer reading too high at the intermediate points when correct at the freezing and boiling points.

It is the usual practice to have the whole of the thread of mercury immersed when determining, or when testing, the freezing and boiling points. Under ordinary conditions of use, however, it is not generally possible to arrange the thermometer with the whole of the mercury immersed when measuring temperatures, and therefore some portion of the column of mercury would be at a temperature different from

that in the bulb, leading to a definite error unless corrected. An approximate correction may be estimated if it is assumed that the emergent part of the column is not appreciably affected thermally by the immersed part. Referring to the sketch in Fig. 5, let t_1 be the reading on the stem at the beginning of the emergent part, t the temperature reading of the thermometer, and t_a* the temperature assumed for the emergent column. Let x be the required correction. Then if v_0 is the volume of one degree division at zero temperature and m and g the coefficients of cubical expansion of mercury and glass respectively, the volume of the emergent column at temperature t_a is

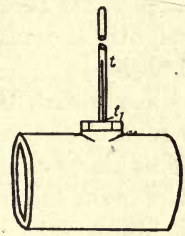


FIG. 5.—Stem of thermometer exposed.

$$v_0\,(t-t_1)\,(1+gt_a),$$

and if raised to the true temperature $(t+x)$ the new volume would be

$$v_0\,(t+x-t_1)\,\{1+g\,(t+x)\},$$

or approximately, since g and x are comparatively small,

$$v_0\,(t+x-t_1)\,(1+gt).$$

The new volume of the column if raised to $(t+x)$ would also be $v_0\ (t-t_1)\ (1+gt_a)\left\{\dfrac{1+m\,(t+x)}{1+mt_a}\right\}$, or again, since m and x are small, this could be written $v_0\ (t-t_1)\ (1+gt_a)\left(\dfrac{1+mt}{1+mt_a}\right)$

$$\therefore\ v_0\ (t-t_1)\ (1+gt_a)\left(\frac{1+mt}{1+mt_a}\right)=v_0\ (t+x-t_1)\ (1+gt)$$

$$\text{or, } x\ =\ \frac{(m-g)}{(1+gt)\ (1+mt_a)}(t-t_1)\ (t-t_a)\ .\ .\ .\ (1)$$

or, since m and g are very small compared with unity,

$$x=(m-g)\ (t-t_1)\ (t-t_a) \text{ approximately. } .\ .\ .\ (2)$$

Example :—$t=200°$ C. (392° F.); $t_a=15°$ C. (59° F.)
$t_1=35°$ C. (95° F.).
$m=\cdot00018$ per °C. ($\cdot0001$ per °F.), $g=\cdot000023$ per °C. ($\cdot0000128$ per °F.).

* An estimation of the temperature t_a may be obtained by employing a *Fadenthermometer*, i.e. a thermometer with an elongated bulb placed close to the emergent column. It is the common practice, however, to take t_a to be the surrounding temperature measured at a distance of say three or four inches from the thermometer.

Then, $x=(\cdot00018-\cdot000023)\ (200-35)\ (200-15)$
$=4\cdot8°$ C. ($8\cdot6°$ F. nearly).
Thus, true temperature $=200+4\cdot8=204\cdot8°$ C. ($400\cdot6°$ F.).

A value commonly used for $(m-g)$ is $\cdot00016$, but it varies slightly according to the class of glass used for the thermometer bulb.

Some distillation of the mercury may take place into the space over the mercury. With an emergent stem the vapour is liable to condense and to form small globules detached from the main column. These are difficult to get down to the main column, but if their length is noted an approximate correction can be made to the thermometer reading.

When measuring temperatures it is the common practice to insert a mercury thermometer into a well or pocket, particularly when measuring the steady temperature of a fluid under pressure. The pocket should be as thin-walled as possible, made of brass* or steel, and sufficiently long to project right into the fluid. The hole in the pocket only needs to be slightly larger in diameter than the thermometer stem as the usual type of bulb is rather less in diameter than the stem. In order to increase the thermal contact between the thermometer and the pocket it is best to place a little mercury* in the pocket, though oil will usually serve quite well. Fig. 6 indicates the arrangement of a thermometer pocket in a steam pipe. It should further be remembered that when a single thermometer is inserted at any section of a tube through which a fluid is flowing at a low velocity the recorded temperature may not be a true average for the whole section, and probably would be found to vary in an erratic manner, because of incomplete mixing of the fluid. These effects can be obviated to some extent by introducing a sudden reduction of cross-section at the thermometer, and particularly if a right angle

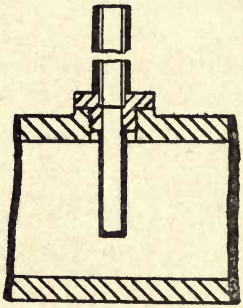


Fig. 6.—Thermometer pocket with guard.

* Mercury should not be used in brass pockets because it attacks the brass.

bend can be introduced before the thermometer is reached. Otherwise it would be necessary to introduce baffles to mix the fluid. Another common source of error not usually recognised sufficiently well by engineers arises if the walls of an enclosure containing a fluid whose temperature is being measured are not at the same temperature as the fluid. Thus, in measuring the temperature of flue gases, for instance, the thermometer (or the pocket if used) should be screened from the radiations emanating from any colder surfaces, as from the boiler shell or tubes. Otherwise the thermometer would read below the true temperature of the gases.*

For general experimental work the bulb of a mercury thermometer should not be larger in diameter than the stem, so that it can be easily inserted into close-fitting holes or pockets. It is also desirable to have the scale graduated so that the lowest reading commonly used is not less than about 3 in. or so above the bulb, so that observations of temperature may be made without having to raise the thermometer from the well or pocket. For laboratory work it is sometimes convenient to have special sets of thermometers for succeeding ranges of temperatures so that the degree divisions may be wider spaced than if one thermometer were used throughout a large range of temperature. For fairly accurate work the thermometer stem should be graduated in half degrees so that estimations of temperature could be made to say, 0·1° F. If the freezing and boiling points do not come on the scale of such special thermometers it is advisable to have them constructed with small enlargements in the stem so that a special mark can be made on the stem to indicate the freezing or boiling points. Three such thermometers are shown in Fig. 7. In the best thermometers the graduations are engraved on the thick stem with a layer of white enamel behind the capillary tube to facilitate observations. Thermometers constructed with scales of porcelain or paper attached to the thermometer

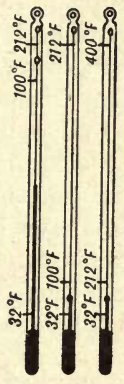


FIG. 7.—Thermometers with different ranges.

* Refer to p. 155 for actual examples of this influence.

stem inside a thin glass covering tube are liable to a displacement of the scale and the thermometer is more fragile than when the scale is engraved on a thick glass stem.

The Bureau International des Poids et Mesures at Sevres, the National Physical Laboratory at Teddington, and the U.S.A. Bureau of Standards at Washington, for a fee will test any thermometer and supply a certificate of corrections. When a fairly large number of ordinary mercury thermometers are used such a course would be too expensive for every thermometer to be certified. One or more standard thermometers could be tested and certified and kept for calibrating the ordinary thermometers in use. The thermometer to be calibrated and the standard one might be inserted together into an oil bath provided with a good stirrer and carefully shielded from draughts. The bath would be heated gently and the comparisons made with slowly rising temperatures,* keeping the oil well stirred. The standard thermometer should have the column of mercury fully immersed so as to avoid stem corrections. Whether the thermometer to be calibrated would also have its stem fully immersed would depend upon the circumstances of its use. If calibrated fully immersed and used with the stem emergent then a stem correction has to be made. It is generally advisable to recalibrate ordinary thermometers periodically as they are liable to slight alterations in their readings in course of time.

From what has been said it will be realised that some difficulty is experienced with ordinary mercury thermometers to ensure an accuracy of measurement within $\pm 0{\cdot}1^\circ$ F., even over the range from freezing to boiling points. Physicists and chemists in the laboratory sometimes work to a much higher degree of accuracy than this by using sensitive and carefully graduated thermometers and by taking some of the special precautions which have been described.

In many cases with which the engineer is concerned, however, it is the accurate measurement of a difference of temperature that is required, as for instance, the increase in the temperature of circulating water flowing through a condenser.

* Comparisons with falling temperatures are generally unreliable because the mercury column is liable to stick.

If the rise of temperature is not more than, say, 30° or 40° F., and no standard thermometer is available for comparison, it is often sufficiently accurate to use two similar thermometers and to compare their readings in a liquid bath, as described on p. 18, over the range of temperature required, for it is found that, even if the thermometers do not read alike, there is commonly a practically constant error of one relatively to the other, and that either of them would indicate the rise of temperature fairly accurately were it practicable to use one thermometer at both the inlet and the outlet. A check can sometimes be obtained by interchanging the two thermometers occasionally during an experiment if the temperatures are quite steady, and then noting the readings.

Some Special Mercury Thermometers.—In the course of the manufacture of ordinary mercury thermometers the tube is sealed off with the bulb and stem heated and full of mercury. On cooling the mercury contracts and leaves almost a perfect vacuum over the column of mercury when atmospheric temperature is attained. A reference to the accompanying table of the vapour pressure of mercury shows that the internal vapour pressure does not introduce any serious variations of internal pressure in the thermometer until fairly high temperatures are attained.

TENSION OF MERCURY VAPOUR.

Temperature									
°C.	50	100	140	180	220	260	300	340	360
°F.	122	212	284	356	428	500	572	644	680
Absolute pressure mm. mercury	·015	·27	1·76	8·54	31·96	96·66	246·7	546·7	785·1

In the case of mercury thermometers intended for the measurement of high temperatures, say, from about 600° F. to about 900° F., it is usual to construct them with an inert gas, such as nitrogen or carbon dioxide, introduced under a suitable pressure in the upper part of the thermometer before the stem is sealed off. This pressure not only prevents an excessive vaporisation of the mercury, and thus reduces the liability of condensation in the upper part of the stem, but maintains a more uniform pressure inside the thermometer. Such thermometers, however, are not usually very reliable. Also, should a bubble of the gas get entangled in the mercury

in the stem, a separation of the column of mercury might introduce a serious error in the readings unless noticed immediately, and it is often difficult to get rid of the bubble.

With a thermometer deeply immersed and fixed in position it is not always possible to see whether the column of mercury is complete, but by careful observation an experimenter can generally judge from the readings obtained, as it is usually the case to expect small variations of temperature during the course of an experiment, and generally there is more than one thermometer to be observed. If the mercury column is broken the top of the column usually sticks for some time at the maximum temperature recorded; but as to whether it ought to record a steady temperature or not can be judged by the readings of the other thermometers, that is, a variation of temperature at one point of an experimental apparatus is usually reflected by similar consequent changes of temperature at other points.

The character of the glass forming the thermometer bulb also limits the temperatures measurable by mercury thermometers. Jena 59^{III} borosilicate glass cannot be used safely above about 500° C. (932° F.), and for Jena 16^{III} the limit is about 450° C. (842° F.). Under the internal pressure the bulb is liable to a permanent increase of volume above these temperatures.

Several thermometers of various kinds have been developed having metal tubes in place of glass, particularly for use at high temperatures, some using a liquid or a vapour, or gas, of which the relation between the pressure and temperature is known, and the bulb is connected up to a kind of pressure gauge with the scale graduated in temperature units. Fig. 8 illustrates such a thermometer made by the Cambridge Scientific Instrument Company for the measurement of the temperature of superheated steam and for similar purposes in ordinary industrial practice. The instrument consists of a steel bulb or chamber which is subjected to the temperature and is connected by steel capillary tubing to the index. The index is a Bourdon pressure gauge having a temperature scale and can be supplied with a recording chart instead of a pointer. The bulb and capillary tube are filled with mercury under

pressure and the system is hermetically sealed. Owing to the smallness of the bore of the capillary tube the index or recording instrument can be placed up to 75 ft. or so from the bulb. When a liquid such as mercury is used, filling the bulb and capillary tube, any difference of level between the bulb and the index or indicator should be allowed for in fixing the pointer. Although such instruments are fairly reliable up to about 1000° F. for the purposes for which they are used it is desirable to have them calibrated periodically.

The Bristol Company also make similar recording ther-

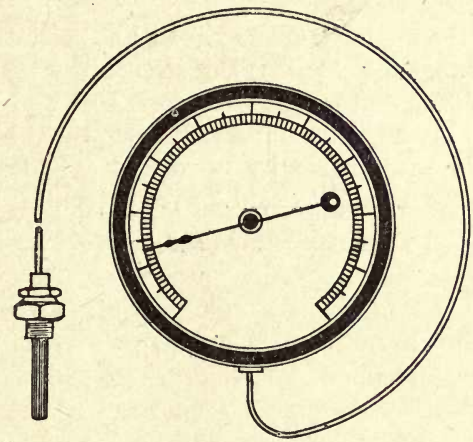


FIG. 8.—Index type of thermometer.

mometers. In their Class I thermometers the instrument is filled with a suitable liquid and is used for temperatures up to 150° F. In Class II it is filled with a vapour, and used between 90° F. and 500° F. In their Class III thermometers the bulb and tube is air or gas filled and can be used between −60° F. and 800° F. The recorders are simply recording pressure gauges arranged with a temperature instead of a pressure scale, and in the Class III thermometers the recorder has a compensating device which corrects for any changes of temperature of the recorder and connecting tube, and are further compensated by proportioning the size of the bulb so as to secure a certain predetermined ratio between the volume

of the gas in the bulb and the volume of the gas in the connecting tube.

Mr. E. F. Northrup* advocated the use of the expansion of molten tin in a graphite bulb and stem for some industrial purposes. Tin melts at 232° C. and does not evaporate appreciably at 1680° C. Molten tin does not form any carbide with graphite and remains pure in a CO atmosphere. It expands uniformly with temperatures up to 1680° C. and probably continues so up to 1800° C. A sheath of carborundum can be used to prevent oxidising of the graphite bulb. The expansion of the tin up the stem of the thermometer is measured by electrical contacts.

So far only the mercury thermometer has been discussed in detail. In subsequent chapters the other important methods of measuring temperature will be described and discussed. Thermometers intended to measure temperatures higher than that commonly measurable by means of ordinary mercury thermometers are usually termed "pyrometers."

* *Production of High Temperature and its Measurement*, Faraday Society, 1917.

CHAPTER III

ELECTRICAL THERMOMETERS AND PYROMETERS

Electrical Resistance Thermometers.—The electrical resistance of a pure metal increases with an increase of temperature. This property may be used to measure temperatures provided the relation between the resistance and the temperature is known and remains invariable. The choice of metals for this purpose is very restricted because of the difficulty of preserving an invariable relation between resistance and temperature in any particular specimen of wire, and for high temperatures is further limited to the platinum series. Siemens* first proposed the platinum resistance thermometer and employed it principally in metallurgical operations, but it was abandoned because the resistance of the platinum wire was found to alter seriously after prolonged or repeated exposure to high temperatures. The Siemens' pyrometer consisted of platinum wire wound on a cylinder of fireclay, with platinum leads to the thermometer head. These were surrounded by an iron sheath to protect the wire from the action of gases at high temperatures.

The permanent alteration of the resistance of platinum wire under such conditions was examined by a committee of the British Association,† and it was discovered that when the platinum wire was surrounded by a platinum sheath no serious permanent change of resistance occurred due to high temperatures. It was found that a permanent change took place if the platinum wire coil were enclosed in an iron sheath and subjected to high temperatures, due to the reducing action of the gases produced by the iron sheath causing the platinum to combine

* *Phil. Mag.*, Vol. XLII, 1871.
† *Brit. Assoc. Report*, 1874.

to some extent with reduced silicon taken from the fire-clay cylinder.

Professors Callendar and Griffiths* experimented with the platinum resistance thermometer and after careful investigation came to the conclusion that pure platinum, when not subjected to strain and when carefully handled, always possesses the same resistance at the same temperature. As now constructed by the Cambridge Scientific Instrument Company the fine platinum wire, about ·008 in. diameter, is wound on a mica frame made of two strips of mica fixed so as to form a + in section, and the wire touches the serrated edges of the strips. The construction is represented in Fig. 9. The four leads to the head of the thermometer may be of copper or silver if it is to be used only for moderate temperatures, or of platinum for high temperatures, and these leads are insulated by mica washers which also prevent convection currents of air in the tube. In place of the platinum wire coil some makers prefer to use platinum strip as it responds more readily to changes of temperature.

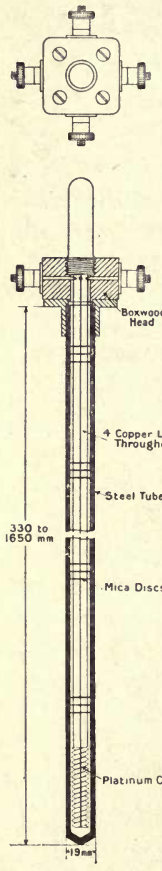


FIG. 9.—Platinum resistance thermometer.

From his experiments Professor Callendar showed that mica has no chemical action on platinum, but it has the disadvantage that it tends to crumble when subjected to temperatures above 900° C. (1652° F.) for lengthy periods. It is found, however, that about 1000° C. (1832° F.) is about the useful limit of a coil of pure platinum wire with platinum leads, for when subjected to higher temperatures the platinum is sometimes liable to permanent changes of resistance, though occasional temperatures may be observed for short periods as high as 1200° C. (2192° F.) without

* *Phil. Trans. Royal Soc.*, Vol. CLXXVII, 1888. *Phil. Mag.*, February, 1899.

subjecting the instrument with platinum leads to serious damage. Professor Callendar also found that all joints in the thermometer itself should be made by fusion because metallic solderings are volatile at high temperatures and attack platinum.

The protecting sheath may be glass, steel, quartz or silica, or porcelain, according to the highest temperature to be measured. A glass sheath may be used up to about 300° C. (572° F.), an iron sheath up to about 700° C. (1292° F.), and a silica or glazed porcelain sheath up to about 1200° C. (2192° F.) if the leads to the thermometer head are of platinum.

Messrs. Siemens Bros. wind the platinum-resistance wire upon a cylinder of highly refractory material, protected from chemical action by a platinum shield, and this is enclosed in an iron sheath.

Professor Callendar suggested the following notation and terms for convenient use in platinum resistance thermometry and these are now generally adopted.

The Fundamental Interval is the increase of resistance ($R_{100}-R_0$) between 0° C. and 100° C.

The Fundamental Coefficient is the average increase of resistance per degree Cent. between 0° C. and 100° C. divided by the resistance at 0° C, thus,

$$\frac{R_{100}-R_0}{100R_0}=\frac{1}{100}\left(\frac{R_{100}}{R_0}-1\right) \quad \ldots\ldots (1)$$

The Fundamental Zero is the reciprocal of the fundamental coefficient with minus sign, thus,

$$-\frac{100R_0}{R_{100}-R_0} \quad \ldots\ldots\ldots (2)$$

and this represents the temperature on the platinum scale of the thermometer at which its resistance would be zero.

$$\text{Platinum Temperature}=p_t=\frac{R_t-R_0}{R_{100}-R_0}\times 100. \quad \ldots (3)$$

The Difference Formula expresses the relation between the temperatures on the gas scale t° C. and on the platinum scale p_t.

$$t-p_t=\delta\left\{\left(\frac{t}{100}\right)^2-\frac{t}{100}\right\} \quad \ldots\ldots (4)$$

The value of the constant δ depends principally upon the purity of the platinum wire and it should be noted that the above expression vanishes when $t=0°$ C. and 100° C. Therefore δ may be determined by an observation at some known temperature, usually the boiling point of sulphur, 444·5° C. (832° F.) at normal atmospheric pressure. Professor Callendar determined the boiling point of sulphur on the gas scale with great accuracy. This was necessary because a small error at this temperature would introduce an appreciable error at 1000° C.

Comparisons made by various experimenters between the gas and the platinum thermometers have shown that the difference formula 4 holds with a high degree of accuracy up to the highest limit of the platinum thermometer when using pure platinum ($\delta=1·5$). At temperatures below −40° C., however, the formula gives too low a reading, amounting to about 2·3° C. at −190° C.

It does not strictly hold, however, for impure platinum when calibrated by the Callendar method, viz. the freezing and boiling points of water and the boiling point of sulphur. The following table* exhibits the corrections necessary at various temperatures for δ varying from 1·525 to 1·90.

Temp. °C.	Correction in ° C for values of δ.						
	1·525	1·550	1·575	1·600	1·700	1·800	1·900
200	+ ·02	+ ·05	+ ·08	+ ·10	+ ·16	+ ·20	+ ·21
400	+ ·00	+ ·00	+ ·01	+ ·03	+ ·14	+ ·29	+ ·37
600	− ·09	− ·18	− ·30	− ·40	− ·88	− 1·42	− 1·96
800	− ·90	− 1·65	− 2·24	− 2·70	− 4·4	− 5·8	− 7·1
1000	− 3·3	− 5·2	− 6·8	− 8·2	− 13·1	−17·1	−20·8
1100	− 5·5	− 8·1	−10·3	−12·2	− 18·7	−24·3	−29·1

If thermometers of impure platinum wire are calibrated at a fourth temperature, say, the silver freezing point, and the difference coefficient δ of the Callendar formula (3) is written $\delta=a+bt$, then this scale is very nearly in agreement with that of a thermometer of pure platinum.*

Measurement of Resistance.—The resistance of the platinum

* *Platinum Resistance Thermometry at High Temperatures*, Waidner and Burgess, U.S.A. Bureau of Standards. Reprint No. 124.

coil is usually measured by some form of Wheatstone bridge. The arrangement shown diagrammatically in Fig. 10 is due to Professor Callendar and is used by the Cambridge Scientific Instrument Company. The ratio coils R_1 and R_2 are adjusted to equality and arranged to be approximately the mean resistance of the platinum coil T. The coil T and the leads P are placed on one side of the bridge as indicated and are

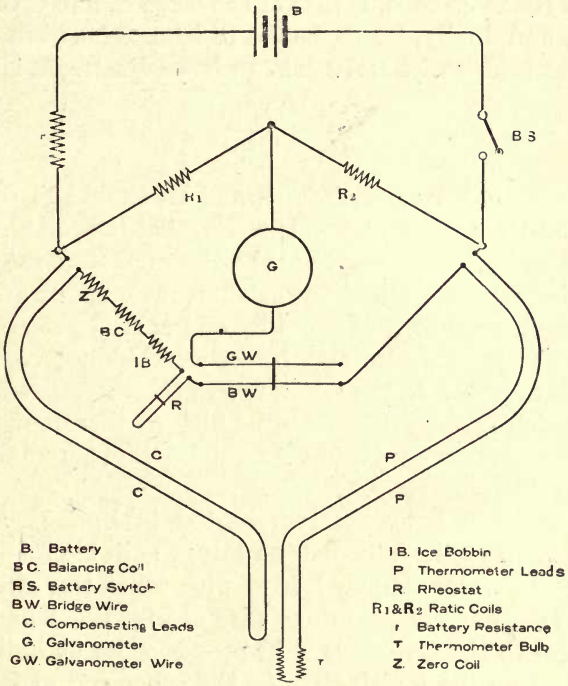


FIG. 10.—Arrangement of Wheatstone bridge for platinum resistance thermometer.

balanced by the compensating leads C, the resistance coils *Z*, BC, IB, and the rheostat R and bridge wire BW. The leads C and P are grouped in one cable and thus all acquire practically the same temperature at any point along the length, with the result that any change of resistance of the leads P is automatically compensated by an equal change in C. The rheostat R is used to adjust the resistance on that side to the

zero conditions, and the ice-bobbin IB is a standard-testing resistance representing that of the thermometer coil T when immersed in ice. To obtain a balance the slider is moved along the wires GW and BW until the galvanometer needle G shows no deflection when the tapping key BS makes contact. The accuracy of this arrangement is, of course, independent of the voltage of the battery.

Let T be the resistance of the thermometer coil, R_1 and R_2 those of the ratio coils, P that of the leads P, and C that of the leads C, and finally, let R_3 be the resistance between the leads C and the bridge wire BW. Then when adjustment is obtained

$$\frac{R_1}{R_2} = \frac{R_3+C}{T+P}$$

It is usually arranged that R_1 and R_2 should be equal, and since P and C are equal it would follow that the coil resistance T is equal to R_3. In order to make thermometers interchangeable the Cambridge Scientific Instrument Company arrange the resistance T so that it changes by one ohm between 0° C. and 100° C. They can also supply an ice-bobbin for each thermometer adjusted to the resistance of the thermometer coil at 0° C., which secures interchangeability of thermometers even when the resistance at 0° C. may be slightly different for different thermometers.

The Whipple indicator represented in Fig. 11 is a convenient form of the Wheatstone bridge suitable for industrial purposes in which a long bridge wire takes the place of the multiple coils and short bridge wire of Fig. 10. The leads are connected to the terminals T in proper order as indicated by the letters on the terminals. At the other end of the instrument the dry batteries are connected to the terminals shown. The pointer or needle of the galvanometer can be seen through the window A. The adjustable resistance consists of a wire wound spirally on a drum which can be rotated by the handle H, and as the spindle of the drum is screwed the rotation causes the drum to travel endwise. A corresponding scale of temperatures is engraved on the drum and can be seen through the window A. The length of the scale is approximately 18 ft. from 0° F. to 2000° F. and thus the average length of

1 deg. Fahr. is over $\frac{1}{10}$ in. The instrument is used in the following manner—All the connections having been made as described, the battery tapping key F is pressed to make contact for an instant and if a correct balance has been obtained the galvanometer needle remains stationary. Usually, of course, an adjustment of the drum by the handle H is necessary to secure a balance, and the direction in which it should be turned to secure the balance is indicated near the galvanometer

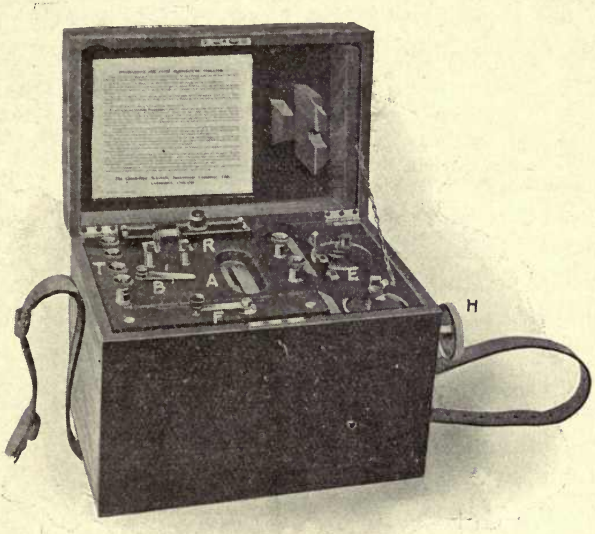


Fig. 11.—Whipple temperature indicator.

needle, i.e. if the needle moves over in one direction the true temperature is higher than that indicated on the scale of the drum at A and the drum is turned accordingly, whilst the movement of the needle in the opposite direction indicates a lower temperature. This procedure is gone through after each movement made in the drum by the handle H until a balance is obtained, care being taken not to keep the tapping key F in contact for more than an instant, so as to ensure a long life for the batteries and to obviate any appreciable change of resistance of the various resistance coils and the thermometer

coil due to the slight heating effect of the flow of current from the battery when the circuit is complete.

The adjustment rheostat R is provided by which the coil resistances can be altered slightly in order to bring the reading on the drum into unison with the actual temperature when the thermometer is at some particular temperature, say, 0° C. Levelling screws are also provided as well as an adjustment for bringing the galvanometer needle to the centre of the scale when neutral. An ice-bobbin for the particular thermometer in use can be connected up on the indicator near the letter R in Fig. 11.

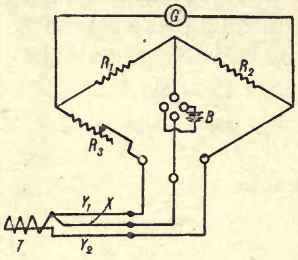


FIG. 12.—Three-lead method of compensation.

There are other methods for eliminating the effect of the variable resistance of the leads besides the one described on p. 27. The one originally adopted by Siemens, for example, and used by several makers, such as Messrs. Siemens Bros. and Co. and Messrs. Leeds and Northrup, is the three-lead compensation. This is represented in Fig. 12 and it is seen that when a balance is obtained at the galvanometer G,

$$\frac{R_1}{R_2}=\frac{R_3+Y_1}{T+Y_2}$$

Since $Y_1=Y_2$ then T would equal R_3, provided $R_1=R_2$.

Although the three-lead method is not quite as expensive in construction as the four-lead method it will be noted that with the three leads there is the greater possibility of thermoelectric effects, unless the leads near the points of connection of the coil T are all made of the same material as the coil.

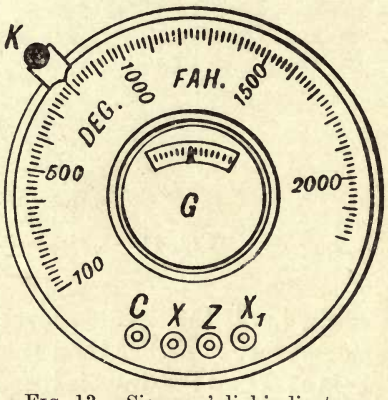


FIG. 13.—Siemens' dial indicator.

The Siemens dial indicator is also based upon the Wheatstone bridge principle, an outside plan view being shown in Fig. 13.

The leads are connected to the three terminals X, X_1, and Z, and the battery to the terminals C and Z, shown in the lower part of the figure. The galvanometer G is mounted in the centre of the dial and round the edge a ring is fixed on which the adjustable resistance is wound spirally. An arm, suitably mounted and movable about the centre of the dial, contains the tapping key K in the battery circuit and the adjustment consists in moving the arm and key round until no deflection is obtained on the galvanometer. The pointed end then indicates the temperature on the scale. The direction of motion of the galvanometer needle indicates in which direction the arm requires to be moved to obtain a balance.

The adjustment to the position of balance in these instruments requires some little time even with a skilled operator, and instruments have been designed which indicate automatically the resistance or temperature of the pyrometer coil by the deflection of a pointer over a scale. Generally speaking, however, such indicators are not quite so sensitive as those based on the Wheatstone bridge or balance method.

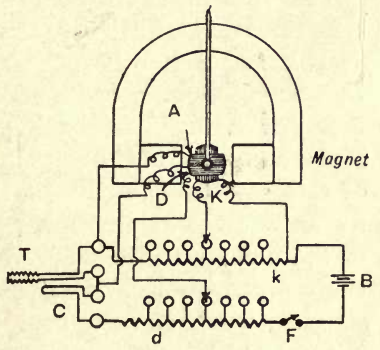


FIG. 14.—Arrangement of Harris-Paul temperature indicator.

One of the most successful instruments of the deflection type for platinum resistance thermometers is the Harris-Paul indicator, made by R. W. Paul, of London. This indicator reads in gas-scale degrees at all ranges of temperature, and its accuracy is independent of the voltage of the battery and of moderate variations in the lengths of the leads. The principles on which it works is shown by the line diagram in Fig. 14. Electrically the indicator is a two-coil ohmmeter. The control coil K and the deflecting coils AD are wound differentially at right angles to each other on a metal cylinder pivoted between the poles of the permanent magnet. A cylindrical iron core is enclosed by the coils without touching them and is stationary. The electrical connections to the

coils are made by flexible ligaments which exert no control on the movement of the coils. The control coil K is shunted with a resistance k, the value of which is determined by the sensitivity required, and may be made to vary simultaneously with the resistance d by means of a double-pole switch. One of the differential windings D is shunted with the resistance d, and the other differential winding A is shunted with the thermometer coil T. The resistance d is variable to suit different temperature ranges of the instrument. These shunted windings are thus connected in series and the circuit is completed through the battery B and key F.

The indicator operates in the following manner: The resistance d is adjusted so that the two differential coils A and D balance each other at some particular resistance of the thermometer coil T corresponding to some particular temperature, depending upon the range of temperature to be measured. If the resistance of the coil T now increases owing to an increase of temperature the current through the winding A increases by an equivalent amount, and this causes a large deflection of the pointer which moves over the scale and thus indicates the temperature. The resistances k and d are made to vary simultaneously so as to compensate for the change of slope in the temperature-resistance curve of platinum at all ranges of temperature. As mentioned previously the range of temperature at which the resistance d would be set would depend upon the temperature to be measured. The object is to make the scale of the indicator very open, the instrument being thereby more sensitive than would be the case if only adjusted for the one range from the lowest to the highest temperatures for which the platinum thermometer is available.

The general appearance of the Harris-Paul indicator is shown in Fig. 15. This is the multi-range portable pattern. A wall pattern is also made and in appearance is similar to Fig. 24, p. 47.

Temperature Recorders.—In many industrial operations, particularly in those associated with metallurgy, a continuous record of high temperatures is most desirable, as many of these operations depend for their complete success upon the close control of the temperature. One form of recorder is illus-

trated in Fig. 16, and was introduced by Professor Callendar for use with platinum-resistance thermometers. As made by the Cambridge Scientific Instrument Company, it consists of a relay mechanism for preserving or restoring the balance of resistances in a Wheatstone bridge circuit, two arms of which consist of a single wire with a slider, and also for recording the resistance of the thermometer on a chart.

The galvanometer carries a contact arm, and this, on swinging to the right or the left, completes an electric circuit. This,

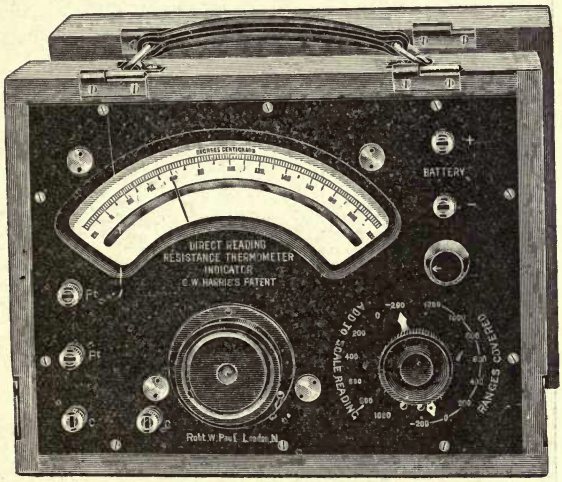


Fig. 15.—Harris-Paul temperature indicator.

through an electro-magnet, removes a brake from a clockwork mechanism which causes a slider carrying a pen to move over the bridge wire until the balance is restored. When the resistance of the thermometer is balanced the galvanometer needle or contact arm will be in a central position, but any change of temperature upsets the balance of resistances, and the galvanometer contact arm, swinging over in one direction or the other, completes the corresponding electric circuit, which then causes the displacement of the slider to restore the balance. The position of the slider is recorded by a pen on the chart driven by clockwork and may be divided into platinum

degrees of equal distance, which can be transferred into ordinary degrees by reference to a conversion table.

One interesting detail is worth a further description. Instead

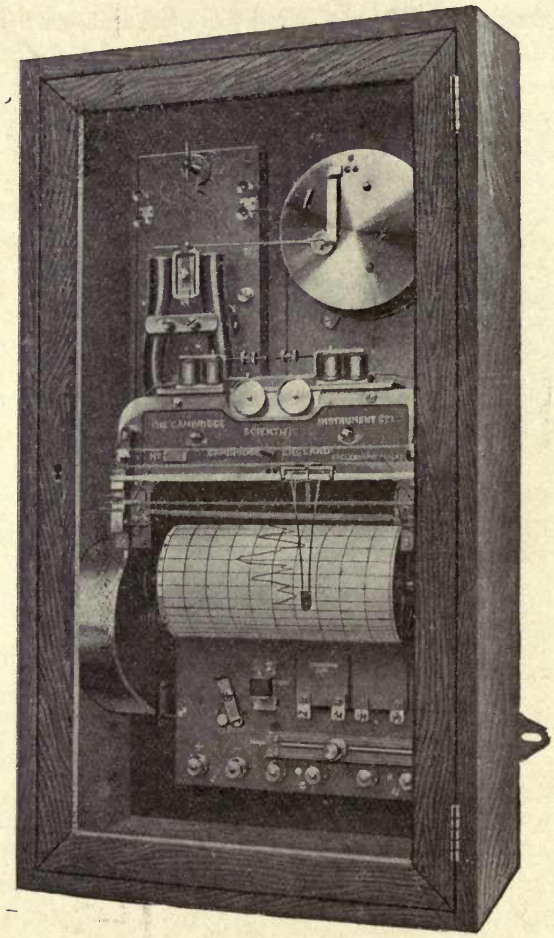


Fig. 16.—Callendar recorder for platinum resistance thermometers.

of the galvanometer needle or contact arm touching a fixed conductor, to which it would tend to stick due to the slight heating by the passage of current, the conductor consists of

the platinum circumference of a wheel which is given a slow rotary movement. This device obviates all tendency to the sticking of the galvanometer needle when in contact, with the result that there is very little lag and the instrument is rendered very sensitive.

Messrs. Leeds and Northrup have developed a recorder on the principles illustrated by Fig. 17. The needle of a differential galvanometer terminates in a platinum end P, normally clear of the blocks S_1, S_2, and S_3. The upper block consists of two pieces of silver, S_1 and S_2, between which is a narrow strip of ivory, I. The lower block, S_3, is also of silver and is raised periodically by an electro-magnetic device not shown in the figure. When the galvanometer is in the neutral or balanced position the tip of the needle is periodically pressed by S_3 into contact with the ivory piece, I, and no current flows since the circuit is incomplete, but if the needle should be opposite either S_1 or S_2, due to the galvanometer being out of balance, the corresponding circuit A or C is completed when P is pressed into contact. By means of electro-magnets and a screw device a slider is moved over a slide wire to restore the balance of resistances in the galvanometer, and a marking pen indicates the position of the slider on the clockwork-driven chart graduated in degrees. It is claimed that the plunger principle of making contacts is much more certain in action than that previously described, where the contact is made by the axial twist of the delicate galvanometer coil.

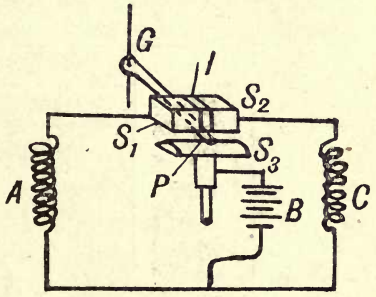


FIG. 17.—Arrangement of Leeds and Northrup recorder.

In an installation of several resistance pyrometers a switch-board may be used in conjunction with a single resistance box and galvanometer, or with a single recorder, whereby a reading or record may be obtained of any thermometer by simply moving the switch to the different contacts.

Care needs to be taken to keep all electrical screwed connections and slider contacts free from dirt and moisture;

otherwise unknown and erratic resistances would be introduced at the points of contact which would be likely to upset completely the accurate measurement of the resistance of the platinum coil.

Sources of Error.—It was mentioned on p. 29 that, in observing the temperature, the tapping key of the instrument should not be kept in contact for more than an instant so as to obviate any appreciable error which might be introduced by the slight heating of the platinum coil by the passing current. The error due to the heating effect of the current, however, is very small and practically negligible for ordinary conditions of operation, as is shown by the following values,* where the normal current through the coil of a particular thermometer was ·01 ampere.

Amperes through coil.	Heating of Platinum Coil above surrounding temperature.		
	At 0° C.	At 100° C.	At 444·5° C.
·0025	·001 ±	·001 ±	—
·005	·004	·002	—
·01	·011	·01	—
·025	·095	·095	·067
·05	·41	·41	·29
·10	1·65	1·69	1·20

Further, the platinum thermometer as usually constructed is not adapted to follow changing temperatures very closely since it is nearly always necessary to use a sheath, and this of itself introduces an appreciable lag. Thus it is best suited for measuring a comparatively steady temperature. Care should also be taken that metallic vapours or furnace gases do not gain access to the platinum coil, or contamination of the platinum may result, with a consequent alteration of its resistance. Therefore a cracked or defective sheath should be replaced immediately. The value of the constant δ in the formula (4), p. 25, may be taken as a measure of the purity of the platinum in the thermometer coil, having a value near 1·5 for pure platinum. Within limits the same formula expresses the relation between the actual and platinum

* *Platinum Resistance Thermometry at High Temperatures,* Waidner and Burgess, U.S.A. Bureau of Standards. Reprint No. 124.

temperatures for impure platinum,* but the value of δ is found to be greater than 1·5, and with impure platinum there is greater liability to a permanent change of resistance on being subjected to high temperatures than occurs with pure platinum, most probably due to the vaporisation of some of the impurities.

When a thermometer is placed in position the coil should be completely immersed, and this can be tested by noting whether various degrees of immersion have any appreciable influence on the observed temperature. It is always advisable to support the thermometer in a vertical position where it is not likely to be damaged by any operations conducted in the neighbourhood of the thermometer, but if it should be necessary to place it in a horizontal position with a considerable length of the heated portion projecting, the heated end should be supported. In any case, careful handling is always essential since the platinum coil and the insulation are very fragile when subjected to high temperatures.

Some makers supply outfits for the checking of the readings of resistance-thermometer indicators and coils. As previously stated the Cambridge Scientific Instrument Company furnish what are called "ice-bobbins," by means of which the resistance of the thermometer may be checked at 0° C. Messrs. Leeds and Northrup supply a series of coils corresponding to definite temperatures on the indicator.

The various connections and leads are liable to introduce disturbing thermoelectric effects in the circuits, but this is only troublesome when the aim is to obtain a high degree of accuracy. With a sensitive galvanometer the thermoelectric effect, if any, can be seen by closing the galvanometer circuit when the battery circuit is open, and the error may be allowed for by reversing the battery circuit and taking the mean reading of the measured resistance. The insulation of the connections, leads, galvanometer, etc., should prevent any accidental leakage from neighbouring lighting or power circuits from interfering with the reading of the instrument.

With reasonable care the platinum resistance thermometer is capable of great accuracy from low temperatures to the

* The temperature corrections necessary with impure platinum coils are given on p. 26.

highest temperature for which it is suitable, and in fact it may be used to calibrate other types of thermometers with a fair degree of accuracy.

Nickel wire may be used instead of platinum for temperatures below about 350° C. (662° F.) and is a much cheaper material. Such thermometers are supplied by several makers, as, for instance, Messrs. R. W. Paul and the Foster Instrument Company.

Thermoelectric Pyrometers: General Principles.—The contact or junction of two dissimilar metals produces a small electromotive force which, under certain conditions, is a function of the temperature and of the metals employed. When the junction forms part of a closed circuit a current of electricity will flow round the circuit provided the electromotive force (e.m.f.) is not balanced by an equal and opposite e.m.f. in some other part of the circuit. It is evident that the circuit can only be completed by joining together the free ends of the two dissimilar metals either directly or through some other conducting material, and these other junctions also give rise to their corresponding e.m.f.'s. Consider first the case of direct connection represented by Fig. 18. The junction at B produces a small e.m.f. say, in the direction of the arrow, and if the other junction A is at the same temperature as B an equal but opposite e.m.f. is obtained, but if A and B are at different temperatures the corresponding e.m.f.'s will, with certain exceptions, also be different and a current will flow round the circuit. Thus if E is the resultant e.m.f., R the resistance of the whole circuit, and C the current, then,

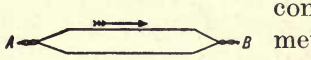


FIG. 18.—Thermoelectric connections.

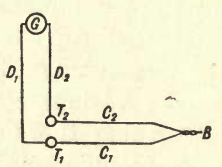


FIG. 19.—Thermoelectric connections with galvanometer.

$$E=RC.$$

It follows, therefore, that if R remains constant the current will be proportional to E and thus C will be a function of the temperature conditions.

A common method of measuring the current is to connect a sensitive galvanometer of large resistance in the circuit, represented in outline by Fig. 19. The two wires C_1 C_2 forming

the junction at B have their free ends connected to the terminals T_1 T_2. Therefore, in the complete circuit there may be several different metals, each pair forming thermo-junctions, as at the terminals T_1 T_2, but if these are all kept at the same constant temperature throughout they would have little or no influence on the consistency of the resultant e.m.f. In other words, provided the various connections or terminals, such as T_1 T_2, were always kept at the same temperature the two arrangements represented by Figs. 18 and 19 are equivalent when the temperature of B is the same in both cases and the temperature of the terminals T_1 T_2 is the same as that of A in Fig. 18, except, of course, the total resistance of the two circuits might be different.

It was Seebeck who made the discovery in 1822 that when a junction of two dissimilar metals is heated an electromotive force is developed. A few years afterwards Becquerel first proposed to use this method for measuring temperatures, and he employed a platinum-palladium couple. Pouillet used an iron-platinum couple, which he compared with the air thermometer. Edmund Becquerel resumed the study of his father's couple (platinum-palladium), and he was the first to direct attention to the necessity of using a galvanometer of high resistance so that any change of the resistance of the heated end of the couple would be practically inappreciable when compared with the total resistance of the circuit.

The results obtained by the various experimenters were very discordant until Le Chatelier, about 1886, and Barus and Tait about 1881, took up the study of thermo-junctions and placed them on a reliable basis. Their investigations showed that the principal source of error was due to lack of physical or chemical homogeneity of the metals used up to that time. For instance, Barus showed that iron, nickel, palladium, and their alloys are unsuitable for the measurement of high temperatures on account of their liability to contamination, or to physical changes introduced by hardening and annealing, which cause parasitic or localised currents to develop, and these interfere seriously with the e.m.f. due to the thermo-junction proper. Barus was led to adopt the

(platinum, platinum 90%—iridium 10% alloy) junction for high temperatures. Le Chatelier showed that platinum-rhodium (10% rhodium) was a very stable alloy at high temperatures and used it in conjunction with platinum.

Owing to the high price of platinum and its alloys many attempts have been made of recent years to produce thermo-couples of comparatively cheap metal wires, so-called "base" metal, such, for instance, as silver-constantan, copper-constantan, iron-constantan, Hoskins couple consisting of nickel wire in conjunction with a nickel-chromium (10% chromium) one. Constantan is an alloy wire, sold commercially as a resistance wire, consisting of copper 60% and nickel 40%. The silver-constantan couple is probably the most satisfactory of the base metal couples below a temperature of about 700° C. (1292° F.). The copper-constantan couple when used with care is fairly satisfactory below about 500° C. (932° F.). The Hoskins (nickel, nickel-chromium) couple may be used up to about 1100° C. (2012° F.) when the wires have been carefully annealed and up to 1300° C. (2372° F.) for short periods. For high temperatures the Hoskins Company also make a nickel-aluminium (2% aluminium) with nickel-chromium (10% chromium) couple, and for low temperatures nickel-copper (65% copper) with nickel-chromium (10% chromium). The Hoskins couples are also made by the Foster Instrument Company, Letchworth. The particular charisteristics of these Hoskins couples are given in detail by Burgess and Le Chatelier.*

Although the (platinum, platinum-rhodium) and the (platinum, platinum-iridium) thermo-junctions or couples are more reliable as regard permanency of readings than any of the other couples, the e.m.f. developed at a given temperature is in general less than the e.m.f.'s given by the base metal couples and therefore necessitate a more sensitive galvanometer to give the same degree of accuracy in the readings. The following table† indicates the approximate relation, the cold junction temperature in all cases being 0° C.

* *The Measurement of High Temperatures.*

† "Modern Methods of Measuring Temperature," R. S. Whipple, *Proc. Inst. Mech. Engs.*, July 29th, 1913.

Name of Thermo-couple.	Approximate E.M.F. in Millivolts at 500° C. (Cold junction at 0° C.)
Platinum, platinum-rhodium 10%	4·4
Platinum, platinum-iridium 10%	7·4
Nickel, nickel-chromium 10% (Hoskins couple)	10·0
Iron, nickel	12·0
Iron, constantan	26·7
Silver, constantan	27·6
Copper, constantan	27·8

Thermoelectric Formulæ.—The relation between the electromotive force E and the temperature t of a thermo-couple is approximately expressed by a formula of the following form, first proposed by Holman,

$$\log E = a \log t + b \quad \ldots\ldots\ldots (1)$$

where a and b are constants depending upon the metals used.

When the cold junction is maintained at 0° C. the following equations express the approximate relations for some of the chief thermo-couples in general use, E being the e.m.f. of the thermo-couple in microvolts, and t the temperature in degrees Cent.

(Platinum, platinum-rhodium 10%), $\log E = 1{\cdot}19 \log t + 0{\cdot}52$ approximate.
(Platinum, platinum-iridium 10%) $\log E = 1{\cdot}10 \log t + 0{\cdot}89$,,
(Silver, constantan) $\log E = 1{\cdot}14 \log t + 1{\cdot}34$,,

When the formula (1) is applicable the thermo-couple only needs to be accurately calibrated at two temperatures in order to determine the values of a and b. When the cold junction is at 0° C. equations of the form $E = a + bt + ct^2$ may also be used over a limited range to represent the relation between the e.m.f. and the temperature.

Until recently one of the greatest drawbacks in thermo-electric work has been the great difficulty of reproducing wires to give the same e.m.f. at the same temperature from different ingots of an alloy. It is a considerable advantage in industrial practice to be able to replace or interchange thermo-couples at any time without having to make a calibration. Messrs. Johnson, Matthey and Company, London, have succeeded in overcoming these difficulties in platinum-rhodium and platinum-iridium ingots and they can now supply the manufacturer of thermo-junction pyrometers with material giving

practically the same e.m.f. at the same temperature as that supplied a few years previously. This cannot be said of the base metal couples, though the manufacturer generally holds a large stock of wire of the same composition.

In the case of some thermo-couples the e.m.f. becomes zero and changes sign at some particular temperature known as the "neutral point." In order to maintain a reasonable degree of sensitiveness it is evidently desirable to use couples in regions remote from their neutral point.

Measurement of Electromotive Force.—There are two methods of measuring the e.m.f. of a thermo-couple, viz. the "galvanometer" method and the "potentiometer" method. On account of its general convenience the first named is used largely in industrial work and also in the laboratory when an extreme degree of accuracy is not required. The potentiometer method, however, is usually more accurate than the galvanometer method, but generally is not as convenient for ordinary work.

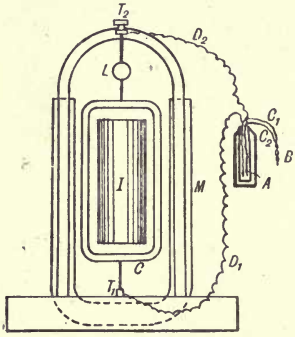


FIG. 20.—Arrangement of galvanometer and thermo-junctions.

Galvanometer Method of Measuring Electromotive Force.—Much of the success of thermo-couple pyrometers is due to the development of the D'Arsonval type of galvanometer for the measurement of the small current generated by the thermo-couple in a closed circuit. This type of galvanometer is illustrated in Fig. 20. The moving coil C of fine insulated wire is suspended between the poles of a permanent magnet M by metallic wires which also serve to conduct the current. When a current is passing the coil tends to turn in the magnetic field, being opposed by the torsion of the suspending wires, and thus it takes up a definite position depending upon the amount of current passing. To intensify the magnetic field a central core of soft iron, I, is fixed between the vertical legs of the coil, and the reading of the instrument is unaffected by moving masses of iron or by stray magnetic fields. The angular displacement of the coil is sometimes measured by a

pointer moving over a scale, but for more accurate work it is usual to have a mirror L on the suspending wire reflecting a beam of light from a suitable lamp on to a semi-transparent scale. Well-designed galvanometers of this type are "dead-beat," that is, torsional oscillations are rapidly damped out.

The resistance of the galvanometer coil or some portion of the circuit should be so high that the indications on the scale are not affected appreciably by any variations in the resistance of the remainder of the circuit which may arise due to changes of temperature or of length. If, for instance, the leads introduced were of considerable length or the pyrometer were inserted at different depths at different times, the variation of resistance so occasioned would probably affect the reading of a low-resistance galvanometer. A mirror galvanometer for pyrometer work with suspended coil may have a total resistance of about 800 ohms and one with a pointer or needle about half this resistance.

For the measurement of the small current the galvanometer needs to be very carefully constructed to be sufficiently sensitive while giving accurate readings under various conditions of atmospheric temperature. The resistance of the movable coil should be practically constant with such variations of atmospheric temperature as are usually experienced since the coil is always part of the circuit, i.e. the coil should preferably be of German silver, or a similar alloy such as manganin, possessing a small temperature coefficient. The coil is, of course, insulated and the spaces between the coil and the magnet and between the coil and the central soft-iron core should be sufficiently large to avoid any accidental friction which would interfere with the free movement of the coil. Although direct contact of the coil is easily prevented, the rubbing of filaments of silk which stand out from the insulation covering has to be guarded against as well as any small accumulation of iron dust on the magnet.

The suspending wire is necessarily of very delicate construction and is usually a flat strip of German silver or phosphor bronze. These not only possess a high elastic limit but have very little permanent change of elasticity. An adjusting screw is generally provided both for the upper and the lower

portion of the suspending wire so that the coil may be adjusted to the zero position, and in making an adjustment care should be taken not to have initial torsion in the suspending wire, which is readily seen by inspection when the suspending wire is a flat strip. A galvanometer should be placed in a position

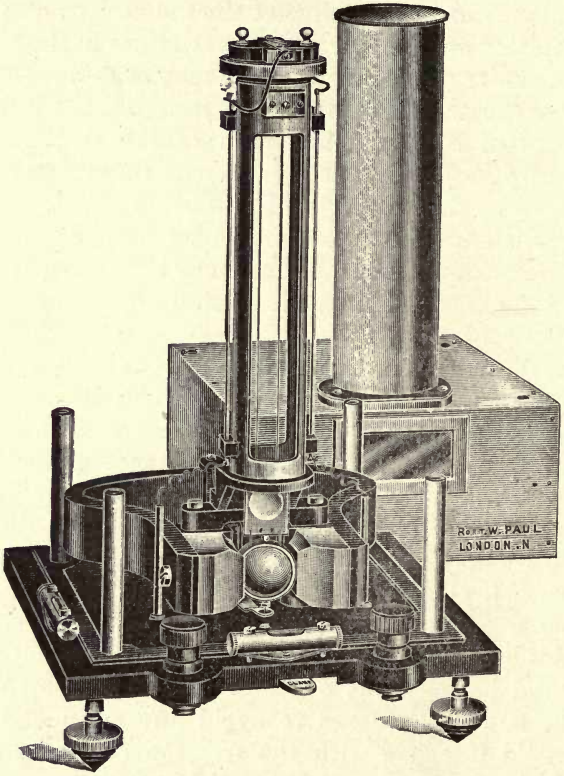


FIG. 21.—Campbell galvanometer with bifilar suspension.

free from vibration or the coil may respond to the vibrations and render accurate readings impossible. The mirror type of galvanometer is hardly serviceable for ordinary works' conditions or on board ship under ordinary sea-going conditions. On board ship the needle type should be suspended in gimbals so as to render a steady reading possible.

The Campbell standard galvanometer, made by R. W. Paul,

is shown in Fig. 21, with the cover removed. Instead of using a strip of metal to give the torsional controlling force the mirror and coil are hung on a wide bifilar suspension. There are thus no errors due to changes of elasticity and there is no creeping of the reading after continuous deflection for a long period. The horse-shoe magnet is laminated and fixed in the horizontal position. Levelling screws are provided so that the coil and suspending wires can be placed truly vertical.

Suspended coil galvanometers furnished with a pointer moving over a scale are now in common use, particularly for industrial work, though the readings are not generally so accurate as those obtainable with a mirror galvanometer, since the

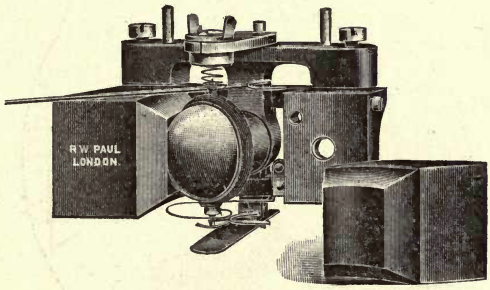


Fig. 22.—Single-pivoted type of galvanometer with pointer.

latter can be made extremely sensitive and the scale as wide as is convenient. The Brown Instrument Company have succeeded in making a high-resistance galvanometer or millivoltmeter of 1000 ohms resistance, the coil, pointer, and springs only weighing ·526 grm. This has been obtained by using aluminium wire ·003 in. diameter with the surface enamelled in place of silk insulation, and using a thin-walled aluminium pointer.

The suspension of the moving coil of a galvanometer is very liable to breakage unless carefully handled, and for ordinary working conditions some makers build pivoted types in which the moving coil and pointer rest in bearings. The turning of the coil is opposed by a hair-spring made of phosphor-bronze which restores the coil to the neutral position when the current ceases. No matter how carefully constructed and handled,

however, the frictional resistance at the pivots is certain to affect the readings and the sensitiveness of the instrument, so much so in fact, that when two pivots are used the galvanometer is hardly suited for use with the platinum series of couples because the e.m.f. is so low in this series.

The single-pivoted galvanometer as made by R. W. Paul,

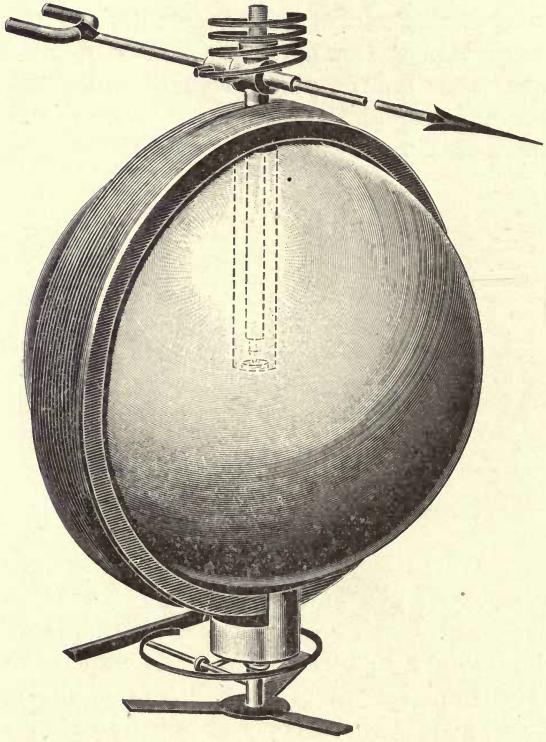


FIG. 23.—Moving parts of single-pivoted galvanometer with soft iron core.

of London, is more sensitive than the double-pivoted type, while preserving a robust construction for industrial use. A circular coil swings concentrically around a spherical core of soft iron, mounted between the poles of a permanent magnet as shown in Fig. 22. The coil, which carries the pointer, is shown detached with its pivot in Fig. 23. The pivot is supported at the centre of the spherical core of iron in a jewel cup,

and in order to protect the pivot from injury by shock when in use, the jewel is mounted on a light spring. The necessity for levelling the instrument before use is avoided by balancing the moving system so that its centre of gravity is precisely at the pivot, and therefore the reading is not affected even if the instrument is tilted slightly. This also makes the instrument serviceable when subject to vibration as on board ship or on locomotives. A cylindrical spiral spring, attached to the coil, provides the controlling force and also carries the current. A flexible ligament connected to the lower end completes the

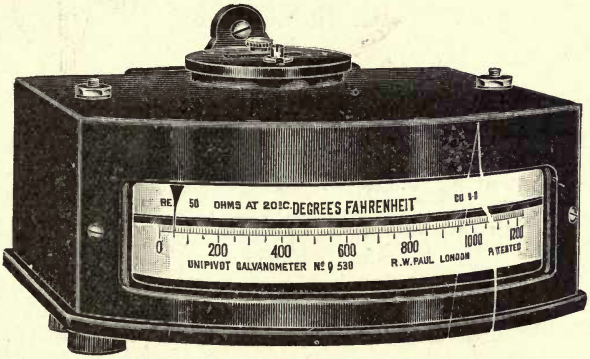


FIG. 24.—Wall pattern of single-pivoted galvanometer.

circuit. When in transit or out of use a clamping arrangement raises the coil from its jewel bearing.

Pivoted galvanometers usually have a lower resistance than the suspended coil type so as to get a larger current and a larger moving force on the coil. In this case the leads should be of a standard length. The coil in the Paul single-pivoted galvanometer has a resistance of about 10 ohms, but a large swamping resistance can be placed in the circuit so as practically to eliminate the varying resistance of leads.

Fig. 24 shows an outside view of this type of galvanometer for attachment to a wall in a permanent installation. Portable patterns are also built on the same principle.

It is well known that spring material is liable to a small alteration of elasticity in the course of time, and this has a correspondingly small influence on the readings of moving coil

galvanometers. Generally it is evident by a slight " creep " causing an alteration of the zero or neutral position. For this reason adjusting arrangements are provided so that the spot of light or the pointer may be brought back to the zero position. With the mirror galvanometer the scale can usually be adjusted sideways to accommodate the zero position, but with pointer galvanometers it is necessary to turn the coil by the adjustments provided for the purpose. The " creep " practically ceases after a few months' use of the instrument and does not recur unless the instrument is badly used or roughly handled.

The ranges of temperature commonly adopted for galvanometers when used with the following thermo-couples are approximately as follows :—

Platinum, platinum-rhodium	0 to 1400	degrees	Cent.
Platinum, platinum-iridium	0 „ 1000	„	„
Nickel, nickel-chromium	0 „ 1000	„	„
Silver, constantan	0 „ 800	„	„
Copper, constantan	0 „ 500	„	„

They can readily be supplied, of course, with the scale readings in deg. Fahr.

When it is desired to use a single galvanometer or indicator with two kinds of thermo-couples adapted to different ranges of temperature, two temperature scales are provided on the galvanometer and the change is effected by altering the series resistance in the circuit.

Many industrial operations are carried out between certain narrow limits of temperature, and then it may be desirable to utilise the whole of the galvanometer scale for this limited range so as to obtain greater accuracy of reading. The electrical connections adopted by R. W. Paul for this purpose are shown in Fig. 25 in conjunction with an electrical cold-junction compensator. The compensator has resistances C_1 C_2 M_1 M_2 arranged to compensate automatically for variations in the temperature of the cold junction in the manner described on p. 61.

The control box has terminals marked I, B, and Indr. for connection to the pyrometer T, battery B, and indicator or galvanometer G respectively. It contains a rheostat A for adjusting the battery current to ·1 ampere, and a switch S

for altering the indicator range. To adjust the current this switch is placed in its central position, and the indicator should then deflect to a red mark on the scale if the rheostat is in correct adjustment. Two temperature scales are marked on the indicator, one of which may correspond to the full range of temperature and the other to the expanded range, or, alternately, two expanded scales can be provided. Either of the two scales is brought into use by setting the switch S to the corresponding mark, which simply alters the resistance in circuit with the pyrometer T. At the same time the connec-

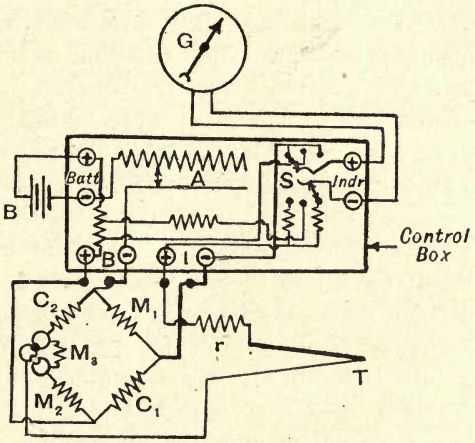


FIG. 25.—Arrangement adopted by R. W. Paul to alter range of indicator G.

tions for the compensator resistance M_3 are altered by inserting a screw into one or other of two positions, this action throwing M_3 into one or other arm of the Wheatstone bridge arrangement.

Galvanometer terminals should preferably be of copper because brass is liable to introduce parasitic thermoelectromotive forces when there are local differences of temperature.

The moving coil type of galvanometer is obviously not suitable for measuring rapidly fluctuating currents such as would be due, for instance, to the fluctuation of temperature of a thermo-junction exposed to the gases in a gas or oil engine cylinder. For such conditions it is usual to adopt the potenti-

ometer method of measuring the e.m.f., but it is possible to measure the current due to the e.m.f. of the junction, therefore giving a measure of the e.m.f., by using the Einthoven type of galvanometer. As built by R. W. Paul, London, this galvanometer has a fine metallic filament placed in an intense magnetic field. The filament carries the current to be measured and is deflected across the magnetic field according to the strength of the current passing. The scale of the deflection and the natural period of oscillation of the filament are adjustable by altering the tension, and the period of oscillation may be made as small as $\frac{1}{2000}$ second, so that there is little danger of the impressed deflection being interfered with by the natural period of oscillation. The deflection of the filament is observed either by a microscope or from an image of the filament projected on to a screen, or a record of the movement may be taken on a moving photographic plate or film.

Potentiometer Method of Measuring Electromotive Force.—The galvanometer method previously described is only suitable for the approximate measurement of high temperatures, and although suitable for many technical and industrial measurements it is usually necessary to have resort to potentiometer methods when a greater degree of accuracy than $\pm 10°$ C. at high temperatures is required. In the potentiometer method use is generally made of a standard cell, or other source of known e.m.f., and a suitable combination of known resistances together with a sensitive galvanometer. If E is the e.m.f. of the standard cell and R the total resistance in circuit with the cell, and if the thermo-couple is connected in series with the galvanometer across the portion r of the total resistance R so that the galvanometer shows no deflection, then the e.m.f. of the couple is $\frac{Er}{R}$.

In practice it is found preferable to balance a portion of a battery or storage cell circuit against the standard cell and then to use this portion of the battery circuit in place of the cell, the balance being obtained immediately before a reading is required. This arrangement is represented diagrammatically in Fig. 26. B represents the battery in series with the variable

resistance R consisting of a combination of coils and bridge wire represented by S_1S_2. Either the standard cell C_e or the hot and cold junctions, H and C, can be placed in series with the galvanometer. The manner of operation is to connect the cell C_e to S_1S_2 by shifting the contacts M_1 and M_2 to S_1 and S_2 respectively. The resistance R is then altered until the sensitive galvanometer G shows no deflection, and then it is known that the difference of potential E between S_1 and S_2 is that of the standard cell C_e. The cell C_e is now replaced by the hot and cold junctions, H and C, having an e.m.f. of value e, M_1 and M_2 being moved until the galvanometer again shows no deflection, a balance being thus again obtained.

$$\text{Then } e = \text{E} \times \frac{\text{resistance } M_1M_2}{\text{resistance } S_1S_2}$$

In practice the current through the potentiometer battery and circuit is adjusted by the variable resistance R to ·01 amp. by balancing the standard cell across a suitable resistance (for a cadmium cell of voltage 1·0185 the resistance is obviously 101·85 ohms). The resistance S_1S_2 in Fig. 26 may consist of 100 equal coils each of resistance ·01 ohm, giving a fall of potential across each coil of 100 micro-volts. A bridge wire in series with the coils would also have a resistance of ·01 ohm and suitably divided into, say, 100 divisions, each division representing 1 microvolt. Thus the main coils can be varied in steps of ·01 ohm and the bridge wire used to give the necessary refinement between each step.

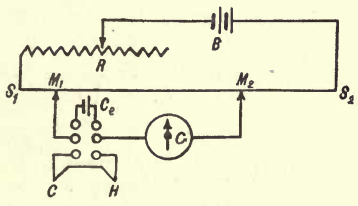


FIG. 26.—Potentiometer method of measuring e.m.f.

Potentiometers of the vernier type may be used to obtain fine adjustment of the resistance. A simple form designed by Dr. Harker has 20 coils, each of resistance ·1 ohm, in series with 11 coils, each of resistance ·01 ohm, in the battery circuit. The battery current is adjusted to ·01 amp. as before described, and thus the drop of potential across each of the 20 coils is 1000 microvolts and across each of the 11 coils is 100 microvolts. A bridge wire of ·02 ohm resistance may be shunted

across any two of the eleven coils and is subdivided into 100 parts, and as this wire carries a current of ·005 amp. each division represents 1 microvolt. The contacts for the various coils are made by mercury cups as these are more suitable for refined measurements of resistance than are plug contacts. Plug contacts have to be kept quite clean and generally have a slightly variable resistance according to the pressure used in placing them in contact, though quite suitable where extreme accuracy is not essential. The thermo-couple is connected in series with a galvanometer across from one of the 20 coils as selected and the bridge wire, and adjustment of the points of contact are made until the galvanometer registers a balance.

Although the galvanometer G may be very sensitive usually there is some little difficulty in finding the true potential balance. If time permits it is always advisable to adjust M_1 and M_2 so that the galvanometer indicator is displaced slightly from the neutral position, first in one direction and then in the other by an equal amount, and then to half the difference. Unless the potentiometer connections are all at the same temperature a slight disturbance may be caused by thermoelectric effects at some of the connections. This influence may be practically eliminated, however, when taking a reading by reversing the battery and thermo-couple connections simultaneously and then taking the mean of the two sets of readings. A similar arrangement of potentiometer is described on p. 137, Fig. 76, in connection with Coker and Scoble's experiments on gas engine temperatures.

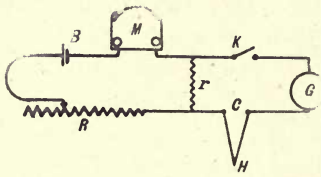


FIG. 27.—Holman's modification of potentiometer.

The modification illustrated in Fig. 27 was first used by Holman. B is a storage cell, M a milliammeter, R an adjustable resistance, H and C the hot and cold junctions respectively, G a sensitive galvanometer, preferably of the mirror type, r a fixed resistance (usually 0·1 ohm). Thus this method does not require a calibrated resistance box or potentiometer, but uses a calibrated milliammeter M instead together with one or

more known resistances. The object is to obtain the e.m.f. between the two ends of the known resistance r and that will be equal to the resultant e.m.f., e, of the hot and cold junctions when adjustment is obtained so that no current flows through the galvanometer G. The procedure is to alter the resistance R until the galvanometer does not show any deflection when the circuit is completed by the tapping key K and then to read the current flowing through the milliammeter M. This current, of course, also flows through the known resistance r, therefore,

$$e = \text{current} \times \text{resistance}.$$

The scale of the apparatus is altered by substituting different values of r.

The relations between the e.m.f. of value e and the temperature of the thermo-junction would be known from previous calibrations at known temperatures, or for approximate work with the platinum series of thermo-junctions it may be sufficient to calibrate at two known temperatures within the region in which the junction is to be used with the cold junction kept at some standard temperature, say, 0° C., and then to make use of the Holman formula, p. 41.

Another arrangement which is used in the "Northrup Pyrovolter" operates on the potentiometer principle combined with the advantages of the direct-reading galvanometer of robust construction for works use. A dry cell is in series with a rheostat, a fixed copper resistance, and a fixed manganin resistance having various tap-offs to alter the scale of the readings. The thermo-couple is connected in series with the galvanometer across the manganin resistance and the resistance of the rheostat is varied until the potential drop across the manganin resistance is equal to the e.m.f. of the couple, the galvanometer showing when a balance has been obtained. The galvanometer resistance is equal to that of the copper resistance in the battery circuit and has the same temperature coefficient. By pressing a button the galvanometer can be inserted in the battery circuit in place of the copper resistance and a direct reading obtained on the galvanometer representing the e.m.f. or the temperature of the thermo-couple.

A simple modification of the potentiometer method, by the Cambridge Scientific Instrument Company, known as "Peake's

Scale Control Board," makes use of the direct reading moving coil galvanometer. It is illustrated diagrammatically in Fig. 28. The battery B causes a current to flow round the closed circuit and the resistances R_3, R_4, and the adjustable resistance R_2, are arranged to give a definite drop of potential across the resistance R_4. In order to adjust this potential drop across R_4 to the standard conditions, which is necessary because the battery voltage may change in course of time, the test coil R_8 and switch S are provided. When the switch S

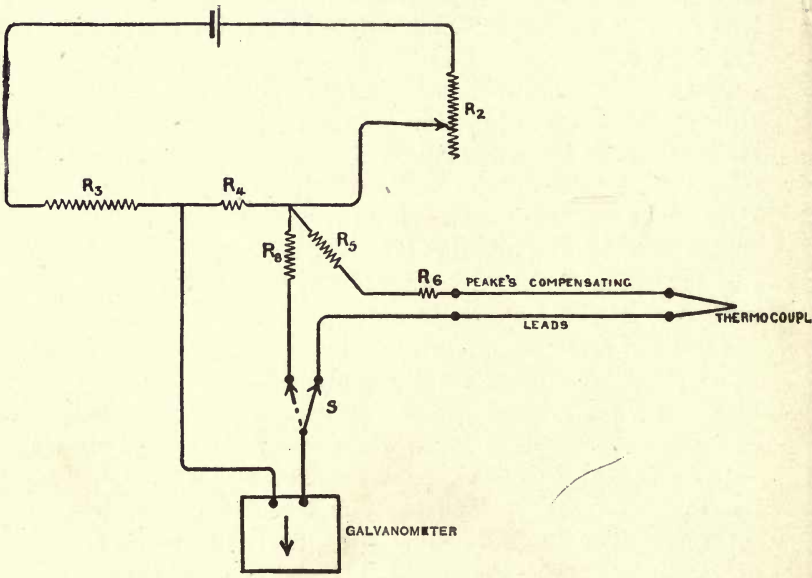


FIG. 28.—Peake's scale control board.

is in the position shown dotted the resistance R_2 is altered until the pointer of the galvanometer is deflected to the extreme position. When the switch S is in the full line position the e.m.f. of the thermo-couple is in opposition to the drop of potential across R_4 and any want of balance, depending upon the temperature of the couple, is recorded on the galvanometer, the scale of which is graduated in degrees. By changing the resistance coils R_4 and R_5 the scale of the galvanometer, and therefore the range of the indications, can be altered and the indicator made very sensitive. Several of these resistance

coils can be obtained giving different ranges across the scale, for example, 0 to 500° C. and 450° C. to 950° C. The purpose of the compensating leads represented in the figure is considered on p. 59.

In the original arrangement introduced by Peake a Clark standard cell is connected across the resistances R_3 and R_4, and when the battery B is at normal voltage the potential drop across R_3R_4 is equal to that of the cell, which therefore does not give any current. If the battery voltage falls, however, the Clark cell gives a small current and thus tends to keep the voltage across R_3R_4 nearly constant.

Several firms build complete potentiometers of compact form which can easily be moved about from place to place.

Standard Cells.*—The Clark cell has been used as a standard of electromotive force for potentiometer work on account of its constancy. Such a cell can be constructed from a small test tube, closed by a cork through which passes a glass tube containing a platinum wire. A quantity of pure re-distilled mercury is placed in the tube so as to cover the end of the platinum wire, and on the mercury rests a paste made by mixing together mercurous sulphate, saturated zinc sulphate, and a little zinc oxide to neutralise it. A rod of pure zinc passes through and is fixed by the cork so as to dip into the paste. The top of the test tube is then sealed with marine glue.

The e.m.f. of this cell at 15° C. is 1·434 volts, decreasing by about ·08% for each rise of 1° C.

The cadmium cell was proposed by Weston on account of its small temperature coefficient and it has now become the standard of reference. In this cell the zinc of the Clark cell is replaced by cadmium, and the negative electrode, instead of being zinc, is made of an amalgam containing about twelve parts of cadmium in a hundred parts of the amalgam. A saturated solution of cadmium sulphate replaces the zinc sulphate of the Clark cell. The rest of the cell is the same.

The e.m.f. E_t volts of the cadmium cell is at t° C.

$$E_t = 1{\cdot}0185 - {\cdot}000038\ (t-20) - {\cdot}00000065\ (t-20)^2.$$

* For detailed instructions regarding the construction of standard cells reference could be made to any standard work on Electricity or Electrical Testing.

When using a standard cell no appreciable current should be allowed to pass through.

The usual construction of thermo-junctions as supplied for general purposes by the Cambridge Scientific Instrument

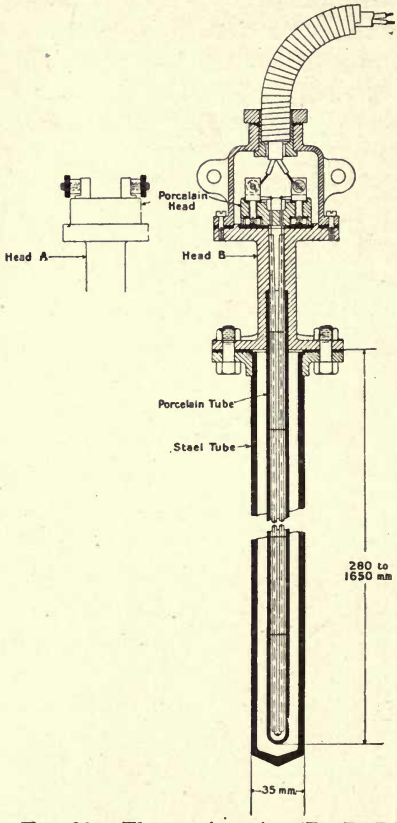


Fig. 29.—Thermo-junction (Pt, Pt-Rh) with porcelain sheath and steel cover.

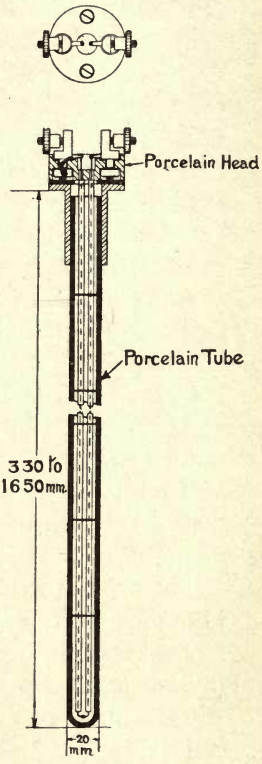


Fig. 30.—Thermo-junction (Pt, Pt-Rh) with porcelain sheath.

Company are shown in Figs. 29, 30, and 31, whilst Fig. 32 shows the method of installing these for the measurement of high temperatures in a furnace. The wires forming the junctions or couples are insulated by thin porcelain sleeve insulators, and to prevent the wires from being contaminated or wasted by the action of furnace or flue gases, etc., a protecting sheath

is used. For temperatures up to about 750° C. (1382° F.) an iron sheath is sufficient, but beyond this temperature up to about 1400° C. (2552° F.)* it is necessary to have a porcelain sheath glazed on the outside, or else to use a quartz sheath. In Fig. 29 the steel sheath forms a protection against accidental rough usage, but it would be removed for temperatures higher than about 750° C., or even for temperatures below this if changes of temperature were anticipated so as to reduce the temperature lag of the thermometer.

The base metal couples are similar in construction, but since they are mainly used for comparatively moderate temperatures an iron sheath is usually sufficient if the couple is formed of wires. The materials being comparatively cheap, some makers also make the hot junction in the rod form, which is of robust construction and does not require a sheath. The most important makers test each thermo-junction and give a certificate for the constants of the junction, or for the payment of a fee the junction would be calibrated at the National Physical Laboratory or at the U.S.A. Bureau of Standards. Such makers are capable of supplying junctions which are interchangeable even though several years may intervene between the dates of manufacture.

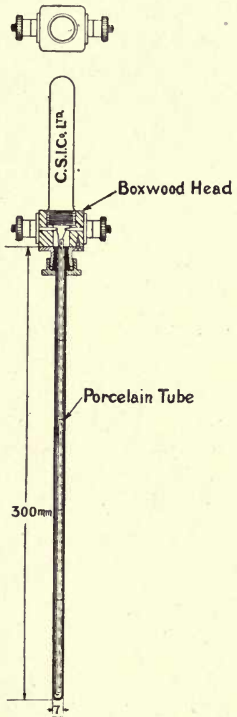


FIG. 31.—Thermo-junction (Pt, Pt-Rh) with porcelain sheath of small diameter.

Junction and Connection of Wires.—The two wires forming the thermo-junction should be soldered or else fused together. Whilst it is true that the manner of contact between the two wires makes no difference to the electromotive force generated, when subjected to high temperatures a couple with the wires merely twisted together is liable to get loosened in course of time, and bad contact results which increases the resistance of the circuit to an unknown degree.

* About this temperature is the useful limit of the platinum series of thermo-couples.

For high temperature measurements the best method of connecting the wires is to fuse them together at the extreme end in an oxyhydrogen flame after twisting the wires together for a short distance. In the absence of such a flame the wires may be soldered with palladium, which can be melted by an ordinary blast lamp if the flame and wires are efficiently protected from radiation losses. Care also needs to be exercised to maintain all screwed connections, such as those at the galvanometer, as clean as possible.

It is desirable to anneal the wires of the couple before the first calibration because any lack of physical or chemical homogeneity sets up parasitic electromotive forces and currents. Also, unless heated to nearly the melting point after manufacture, the e.m.f. of the couple is liable to change in course of time. The annealing can best be done by sending a heating current through the wires. The leads from the couple should be well insulated.

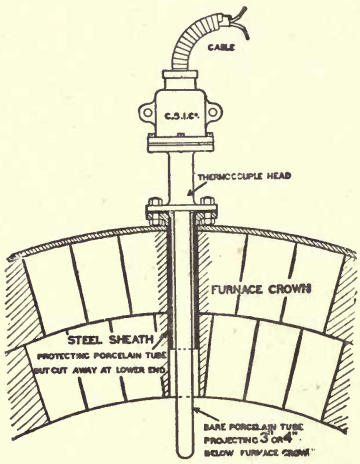


FIG. 32.—Thermo-junction inserted into furnace.

Cold Junction Corrections.—It will have been noticed that in the usual construction of thermo-couples the wires forming the hot junction are connected to the head of the thermometer and the galvanometer leads are commonly connected to the wires in the head by screwed contacts. Unless the head of the thermometer is specially water-cooled so as to preserve practically a constant temperature at this end it is evident that the terminals or connections at the head are likely to acquire a temperature higher than that of the outside leads and measuring instruments. Therefore care has to be taken that no incidental electromotive forces are developed at the thermometer head. Terminal connections should preferably be of opper, as brass is liable to cause parasitic thermo-electromotive forces under varying temperature conditions.

If the external leads were of the same materials as those forming the junction inside the thermometer no appreciable e.m.f. would then be produced at the thermometer head and the cold junction would now be at the outer end of the leads. For reasons of cost, however, it is desirable to use outside leads of cheap wire, and for use with the platinum series of couples Bristol and Peake independently proposed to use leads made of cheap alloys which happened to give practically the same e.m.f. as the platinum and its alloys within the

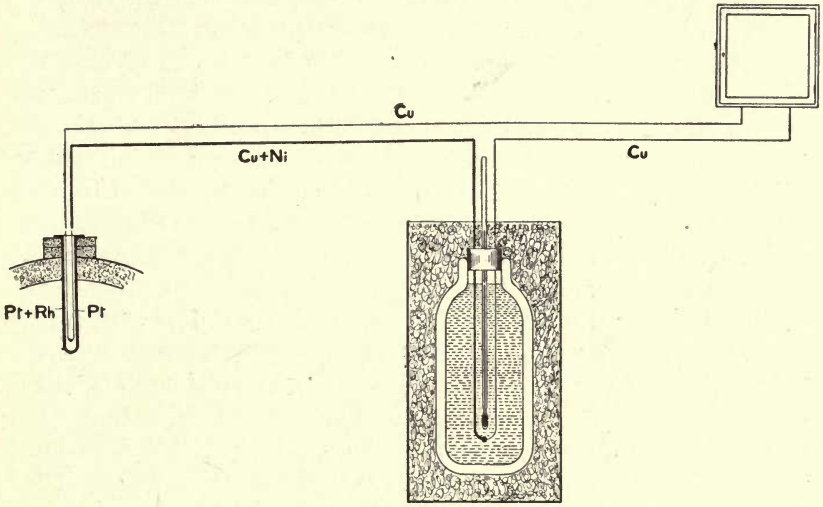


FIG. 33.—Peake's compensating leads.

limited range of temperature anticipated at the head or terminals of the thermometer.

For use with the platinum series of thermo-junctions Peake introduced his compensating leads, one of copper and the other a copper-nickel alloy of suitable composition, giving the same e.m.f. as that given by the platinum and the platinum alloy at the same temperature. Experiments show that the compensation is practically correct for any temperature of the thermometer terminals up to 300° C. The connections in this case are illustrated in Fig. 33. The copper lead has to be connected to the platinum alloy wire and the copper-nickel lead to the platinum wire of the junction to give the proper com-

pensation. The cold junction C is shown placed in a thermos-flask filled with oil and with the leads well insulated. The temperature of the flask is read on the mercury thermometer, which should show very little change of temperature even though the surroundings fluctuated several degrees. For a permanent installation it is often sufficient to place the cold junction in a vessel buried in the ground.

The compensating leads are particularly useful when the pyrometer is necessarily short and the pyrometer head acquires a fairly high and uncertain temperature, and also where the leads are long ; for example, as in measuring the temperature of superheated steam at various points in a range of steam pipes in a central power station, or the steam temperatures at various positions in a large steam turbine, making use of one galvanometer for all the pyrometers through a switchboard.

Unless the temperature of the cold junction happened to be that at which the calibration was made, corrections need to be applied to the readings of the indicator to allow for the cold junction temperature. One approximate method consists of setting the galvanometer or indicator needle at the temperature of the cold junction when on open circuit (the instrument being calibrated with cold junction 0° C.), but although it will give an approximate correction this method is somewhat troublesome. Instead of this a calculated correction may be made. If t_0 is the cold junction temperature for which the instrument reads correctly and t the observed temperature of the cold junction, the correction usually lies between $\frac{1}{3}(t-t_0)$ and $(t-t_0)$ depending upon the type of couple and the temperatures of both hot and cold junctions.* Commonly the pyrometer is calibrated for a cold junction temperature of 20° C. (68° F.).

For example,† in a (Pt, 90 Pt–10 Rh) Heræus couple having for its temperature (°C.)—e.m.f. (millivolts) relation the equations—

$$E \times 10^4 = 56{\cdot}04t + {\cdot}05434t^2 \text{ between } 0° \text{ C. and } 100° \text{ C.,}$$

and,

$$E \times 10^4 = -2820 + 80{\cdot}71t + {\cdot}01694t^2 \text{ between } 300° \text{ C. and } 1500° \text{ C.,}$$

* *Measurement of High Temperatures*, p. 155. Burgess and Le Chatelier.

† *Note on Cold-Junction Corrections for Thermo-couples*, Reprint No. 202 (from Bulletin of the Bureau of Standards, Vol. 9), U.S.A.

with the cold junction at 0° C., it was found sufficient in ordinary pyrometric work to correct for the cold junction temperature, t° C., by adding to the observed temperature, t_1° C., the amount $\cdot 6t$ from 400 to 700° C. and $\cdot 5t$ from 700 to 1400° C., where t was less than 50° C.

An automatic compensator for cold junction temperatures has been devised by The Bristol Company consisting of a small glass bulb and capillary tube filled with mercury up to some convenient point of the capillary tube. A short loop of platinum wire dips into the mercury and forms a part of the circuit. Changes in temperature cause the mercury to change in volume, with the result that a greater or less resistance is cut out of the circuit.

Mr. R. W. Paul uses an electrical cold-junction compensator which can be applied to any thermo-junction pyrometer, and can be made to serve the same purpose as the compensating leads discussed on p. 59. The principle of the compensator is illustrated in the diagram, Fig. 34, which is similar to that of the ordinary Wheatstone bridge. The two arms $C_1 C_2$ of the bridge are of copper and therefore have a large temperature-resistance coefficient, whilst the two arms $M_1 M_2$, of manganin, have practically no temperature-resistance coefficient. The current through the latter arms is limited, by means of the resistance A, to ·1 ampere. The galvanometer, or indicator, circuit includes the thermo-couple T and is joined across KL.

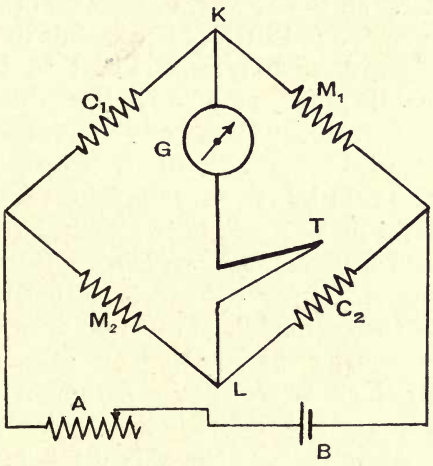


FIG. 34.—Paul cold-junction compensator.

When the temperature of the junction T and all the connections are at the standard temperature 20° C. (68° F.) the bridge is in balance and there is no battery current through the galvanometer. As soon as the temperature of the cold junction varies the bridge is thrown out of balance and conse-

quently a small out-of-balance current passes through the indicator G. The resistances are so proportioned that this current increases or decreases the deflection of the indicator by the amount of the cold-junction error. The use of this compensator in connection with an electrical range setter for the indicator is illustrated by Fig. 25, p. 49.

Several devices have been adopted in the galvanometer itself to compensate for the cold-junction temperature, but these can only be effective when the cold junction is at the galvanometer or has the same temperature as the galvanometer. In the Thwing instruments the correction is obtained by a compound strip of two metals having unequal coefficients of expansion, and so attached to the spring controlling the needle that the reading of the galvanometer is the temperature of the surroundings when on open circuit. A similar compensation is obtained by an arrangement devised by C. R. Darling, and sold by R. W. Paul, where a spiral made of a compound strip of two metals is attached to the galvanometer needle, and coils or uncoils when cooled or heated, thereby moving the pointer over the scale so that it indicates the temperature of the surroundings when on open circuit. On connecting the pyrometer the pointer moves through an amount represented by the difference between the hot and cold junction temperatures and therefore indicates the hot junction temperature.

Temperature Recorders for Thermo-junctions.—For the autographic recording of temperatures Le Chatelier introduced a photographic process whereby the spot of light from the galvanometer mirror fell upon a moving sensitised plate. Sir W. Roberts-Austen also used a similar process for metallurgical research, but the great drawback was the inability of the operator to see the record until the film was developed afterwards. In its more modern form the Roberts-Austen recorder consists of a box enclosure containing the mirror galvanometer and a sheet of sensitised paper wound round a drum which is rotated at a known rate by means of clockwork. By means of a prism rays of light from an external electric lamp are caused to fall on the mirror of the galvanometer, and the reflected ray is split into two portions, one of which passes through a narrow slit on to the moving sensitised paper, and

after being developed the record appears as a continuous line. The other portion falls on to a ground glass scale divided to read temperatures, which can be seen by the operator at any time. This arrangement possesses all the sensitiveness associated with the mirror galvanometer.

For most industrial operations requiring a record of temperatures the above arrangement is too delicate and requires too much attention. The thread recorder, invented by Mr.

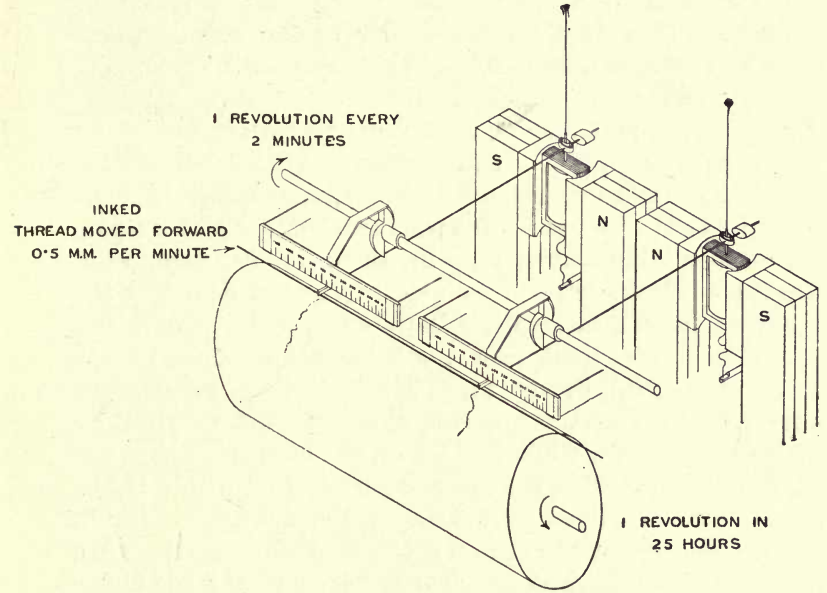


FIG. 35.—Double-thread recorder.

Horace Darwin, may be taken as an example of a recorder suitable for general conditions. A diagrammatic representation of a double-thread recorder is given in Fig. 35. The record paper is wrapped on a drum rotating once in twenty-five hours, being driven by clockwork. Over the top of the drum an inked thread is stretched and this travels lengthwise at a slow rate so as to present newly inked portions of the thread. The pointer of the galvanometer moves just over the thread and under the guillotine bar, but does not touch either until the bar is allowed to drop, which occurs once every two minutes.

The dropping of the bar presses the pointer on to the thread which in turn touches the paper and leaves a mark at the point of depression. Soon afterwards the bar is raised slowly and the pointer is free to take up its proper position ready for the next impression. Thus by this means a record of temperatures is obtained which is practically continuous without introducing any external resistance to the motion of the galvanometer coil and needle.

Most makers of thermo-electric pyrometers are able to supply recorders more or less similar to the one described above, and these can be adapted to give continuous records of temperatures for several pyrometers.

The Brown Instrument Company make an automatic control pyrometer. A thermo-couple of nickel-chromium alloy in the furnace operates a high-resistance millivoltmeter, and under the pointer is a table with two contact pieces separated by insulating material $\frac{1}{32}$ in. thick. A depressor arm, actuated by clockwork or by an electric motor, depresses the pointer at regular intervals, usually every ten seconds, and thereby makes contact below, similar in principle to the arrangement shown in Fig. 17, p. 35. Applied to an electric furnace, contact on the low side closes the main switch by means of a solenoid, while contact on the high side opens the switch, thus controlling the furnace temperature within 20° F. or so. In a modified arrangement the solenoid-operated switch is used to cut out or in a rheostat of suitable resistance in the main circuit. The contacts and insulating piece under the pointer can be shifted along the scale of the millivoltmeter to any desired temperature by turning a knob.

The same form of switch can be used to control a gas or oil-fired furnace. The usual method is to control a by-pass supply only instead of the whole supply of gas or oil, as this is sufficient to control the temperature of the furnace within the limits usually desired. Thus with a 2-in. gas supply pipe a $\frac{1}{2}$-in. by-pass would be introduced and the $\frac{1}{2}$-in. valve in this by-pass would be opened or closed by the switch according to the position of the pointer of the millivoltmeter when depressed into contact.

The same firm have also devised an arrangement for signal-

ling to the fireman controlling the furnace whether the temperature is correct, too high or too low. With a number of furnaces in operation a central pyrometer indicating station may be adopted, and the central operator signals to the fireman by means of light, a red light if the temperature is too low, white light if correct, and a green light if the temperature is too high. The signalling can also be done by means of switches operated automatically, thus dispensing with the central signalling operator.

Unless sufficient care is taken in the design and arrangement of a thermoelectric pyrometer the various connections or contacts may introduce disturbing e.m.f.'s, sometimes of a parasitic nature. For this reason copper terminals or contacts are preferable to brass. All the terminals or contacts should be kept clean or unknown resistances may be introduced at these points. The insulation should prevent leakage from neighbouring lighting or power circuits from affecting the readings. This is particularly necessary at high temperatures when the pyrometer is used in an electrically heated furnace, and in such circumstances a good conductor might be interposed between the measuring instruments and the source of leakage.

CHAPTER IV

RADIATION AND OPTICAL PYROMETERS

Radiation and Optical Pyrometers.—Pyrometers of this class are intended principally for the estimation of temperatures beyond the working limits of the platinum resistance and the thermoelectric pyrometers, say, for temperatures higher than about 1000° C. (1832° F.). Within recent years great developments have taken place in the design and use of radiation and optical pyrometers and fairly reliable estimations of high temperatures, such as occur in furnaces and the like, have been rendered possible since the laws of radiation came to be better understood. The laws of radiation are dealt with at some length in *Heat Transmission by Radiation, Conduction, and Convection*, and where mention is made of these laws in this present chapter no more is given than is required for the understanding of the construction and uses of the particular instruments described. It is proposed to consider in detail only those instruments suitable for the measurement of the temperatures met with in industrial practice ; for a general description of those designed principally for experiments in general physics (sometimes called "radiometers"), reference may be made to any standard work on heat, such as Preston's *Theory of Heat*.

According to the Stefan-Boltzmann law of radiation the total energy radiated per unit area by a "black body"* is proportional to the fourth power of the absolute temperature. Thus a "black body" at absolute temperature τ surrounded by an envelope having an absolute temperature τ_0 loses

* A "black" body was defined by Kirchoff as "a body which is not in the least transparent, and which does not reflect at all, but absorbs all incident radiation of whatever wave-length at all temperatures.

energy by radiation per unit of time proportional to $(\tau^4 - \tau_0^4)$. It is to be noticed that unless τ_0 is very much above the temperature of the atmosphere it has very little influence on the resultant radiation losses when τ is much higher than τ_0. For example, if τ is 2000° C. absolute (1727° C.) and τ_0 is 473° C. absolute (200° C.) the radiation losses would be proportional to $(2000^4 - 473^4)$ or $\propto (160{,}000 - 500)\ 10^8$, which shows that the envelope at 200° C. has hardly any influence on the loss of radiant heat from the black body at 1727° C.

Principles of Radiation Pyrometers.—The energy received by a total radiation pyrometer is usually estimated by directing the energy on to a suitable receiver, generally a small blackened disc. The temperature of the receiver increases nearly in proportion to the energy received, and this is commonly estimated by a thermo-junction soldered to the receiver, and connected to a galvanometer in the manner described in Chapter III. In some instruments the receiver is a bimetallic spiral spring giving an angular deflection with change of temperature.

The quantity of energy falling on the receiver not only depends upon the temperature of the source, but also on the area of surface of the source and of the receiver, on their distance apart, and on their emissive and absorptive powers. In general it is desirable to have the receiver as small as is practicable, principally because the necessary area of the source is thereby correspondingly small; but with a small receiver some condensing arrangement is necessary to concentrate the energy at the surface of the receiver. This is usually obtained either by a convex lens or by a concave mirror, and two different designs of instrument are then possible.

1st. The source and the receiver are located at the conjugate foci of the lens or mirror.

2nd. A front diaphragm of the pyrometer and the receiver are located at the conjugate foci of the lens or mirror.

For general service it is fundamentally important that the pyrometer reading should, within limits, be independent of the distance from the source to the receiver, and this necessitates a constant value for the solid angle of the cone of rays from the source ultimately falling on the receiver. To fulfil this condition in case No. 1 the pyrometer has to be provided

with a focusing arrangement whereby the distance from the lens or mirror to the receiver may be varied to suit the distance from the source to the lens. In case No. 2 the front diaphragm becomes the secondary source and the foci are definitely fixed, and therefore no focusing adjustment is required in this arrangement.

Case No. 1. Fig. 36 illustrates diagrammatically the lens

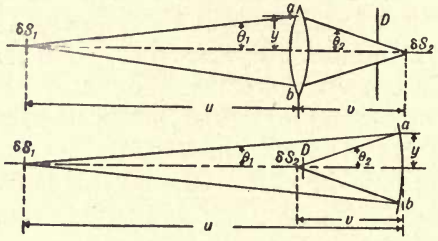


FIG. 36.—Radiation pyrometers of variable focus.

and mirror types of radiation pyrometer with variable focus.

Let δS_2 = area of receiver.

,, δS_1 = area of cross-section of source of which δS_2 is the image.

,, u = distance of source from lens or mirror.

,, v = distance from image to lens or mirror.

,, i_1 = intensity of the radiation of the source.

Then, the total energy I_1, in the cone $a\,\delta S_1 b$ is given by,

$$I_1 = 2\pi i_1 \delta S_1 \int_0^{\theta_1} \sin\theta \cos\theta \, \delta\theta = \pi i_1 \delta S_1 \sin^2\theta_1 \quad . \quad . \quad . \quad (1)$$

A similar expression applies to the image space,

$$I_2 = \pi i_2 \delta S_2 \sin^2\theta_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If there were no loss of energy by absorption and reflection, equations (1) and (2) would be equivalent. By the condition of magnification of the optical system $\frac{\delta S_1}{\delta S_2} = \frac{u^2}{v^2}$, and since $\sin^2\theta_1 = \frac{y^2}{u^2}$ nearly, and $\sin^2\theta_2 = \frac{y^2}{v^2}$ nearly, then $i_2 = i_1$ nearly.

When some of the radiation is absorbed by the lens or mirror (and reflected also in the case of the lens), i_2 is less than i_1.

For all practical purposes, however, i_2 may be taken to be proportional to i_1.

Thus, $$I_2 = ci_1 \sin^2\theta_2 \quad \ldots\ldots\ldots\ldots\ldots (3)$$

where c is a constant.

Therefore I_2, the radiation absorbed by the receiver, can only be independent of the focusing distance when $\sin^2\theta_2 =$ constant $= \frac{y^2}{v^2}$ (nearly).

$\sin^2\theta_2$ is made constant by fixing the angle θ_2 at a constant value by means of a diaphragm or pupil D at a certain distance from δS_2, and when this is done, the energy falling upon the receiver is proportional to the intensity of the radiating source. The pyrometer readings are then nearly independent of the

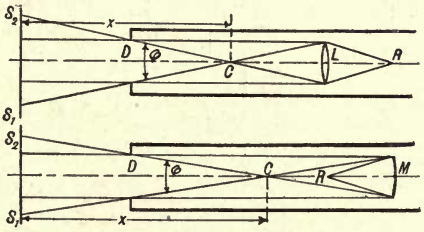


FIG. 37.—Radiation pyrometers with fixed focus.

focusing distance, provided the source is of sufficient size to ensure that the image completely covers the receiver δS_2 for all conditions.

The conditions for case No. 2 are represented diagrammatically in Fig. 37. The diaphragm D acts as a secondary source, and the conjugate foci of the lens or mirror are situated at D and at the receiver R, the instrument therefore having a fixed focus. It is obvious from geometrical considerations that the smallest diameter of the source S_1S_2 which can be used without requiring correction of the readings of the pyrometer will be

$$S_1S_2 = \frac{x \times (\text{dia. of diaphragm D})}{DC}$$

where x is the distance from the source to the point C. The angle θ is called the angular aperture of the instrument.

The Féry radiation pyrometer shown in section in Fig. 38 represents the adjustable focus type of instrument. The concave mirror C is attached to a focusing rack so that it can be adjusted in the metal case by means of the focusing pinion. The rays received by the mirror are reflected on to the blackened thermo-junction consisting of a very small copper or silver disc to which the wires forming the junction (usually either copper-constantan or iron-constantan) are soldered, and the mirror is adjusted until the focus coincides with the receiver disc. The mirror is usually about 6·8 cm. diameter, 7·5 cm. focal length, and 15 cm. radius of curvature.

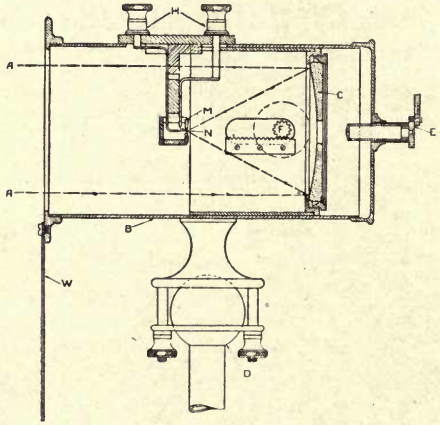


Fig. 38.—Féry radiation pyrometer.

It is sometimes made of glass with a gilt reflecting surface, but a better arrangement is to make the mirror of copper with an electrolytic deposit of gold (polished) as the reflecting surface. The high thermal conductivity of copper tends to reduce the lag of the instrument as compared with a glass mirror, because the copper acquires a steady temperature more rapidly than glass.

The heating of the thermo-junction induces an electromotive force, usually measured by means of a sensitive galvanometer or millivoltmeter of high resistance connected by leads to the terminals on the pyrometer, and the scale of the galvanometer may be graduated to indicate the temperature of the

source. The potentiometer methods of measuring e.m.f. described on p. 50 can also be used, with a corresponding increased degree of accuracy, since the readings are then practically independent of the resistances of the thermo-junction, leads, and galvanometer.

In order to give a clear indication as to when the receiver disc with its thermo-junction is in the focus of the mirror C, small semicircular mirrors M, inclined to one another at an angle of from 5° to 10°, are fixed near the junction, and these divide the image of the sighted object or source into two semicircular portions as indicated by Fig. 39, where the central illustration shows the appearance when in focus and the other two when an adjustment of the focus is necessary. These focusing mirrors are either of glass, silvered or gilded, or of copper, gold-plated, and an opening of about

FIG. 39.—Focusing indicator on Féry radiation pyrometer.

1·5 mm. diameter at the centre of these mirrors forms the limiting diaphragm immediately in front of the receiver disc or thermo-junction.

A sectored diaphragm, which is adjustable, may be placed on the open end when high temperatures are being measured, say, above 1500° C. (2732° F.), so as to cut off a definite proportion of the radiations. This merely alters the scale of the readings on the galvanometer and prevents excessive heating of the junction. Formerly this diaphragm was blackened, but this absorbed a considerable amount of energy, some of which was radiated from the back face on to the receiver. To overcome this defect the diaphragm should be water-cooled or else gold-plated.

As soon as the junction attains a steady temperature the radiant energy absorbed by the receiver is dissipated by conduction, convection, and radiation to the surroundings at an equal rate, and it is generally assumed that the rate at

which it loses energy is approximately proportional to the difference of temperature between the hot and cold junctions.

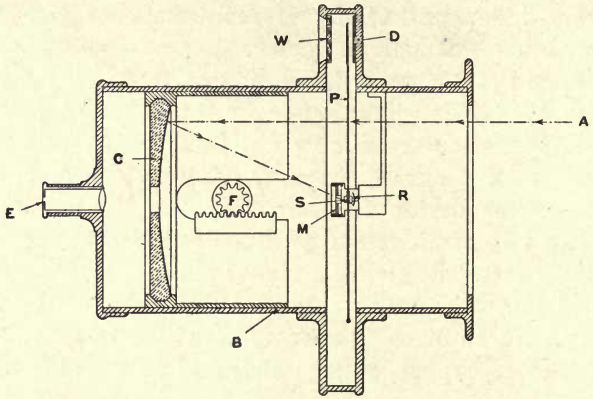


Fig. 40.—Féry radiation pyrometer with spiral spring and pointer.

In other words, the excess of temperature of the hot junction over its surroundings is taken as a measure of the energy received. The indicator or galvanometer is usually graduated to read directly the temperature of the source on the basis of these principles. Within limits the rate at which the receiver absorbs energy is nearly independent of the distance between the instrument and the sighted object or source because it is arranged that the image of the source more than covers the receiver. The thread recorder (see p. 63) can be used with this instrument to obtain a continuous record of temperatures. A cheaper and simpler form of the Féry pyrometer is shown in Fig. 40, where a bimetallic spring R with the attached pointer P replace the thermo-junction and galvanometer. The spring and pointer are shown four times full size in the separate illustration, Fig. 41. The radiations from the source are focused, in the manner previously described, on the spiral spring R, and being formed of two strips of metal soldered

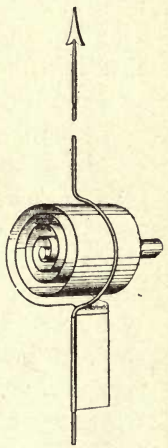


Fig. 41.—Spiral and pointer of Féry pyrometer.

together and having two different coefficients of expansion, the spiral uncoils as its temperature increases, thus moving the pointer over the scale D. This scale is graduated to read the temperature of the source and is observed through the window W. The general appearance of this instrument is

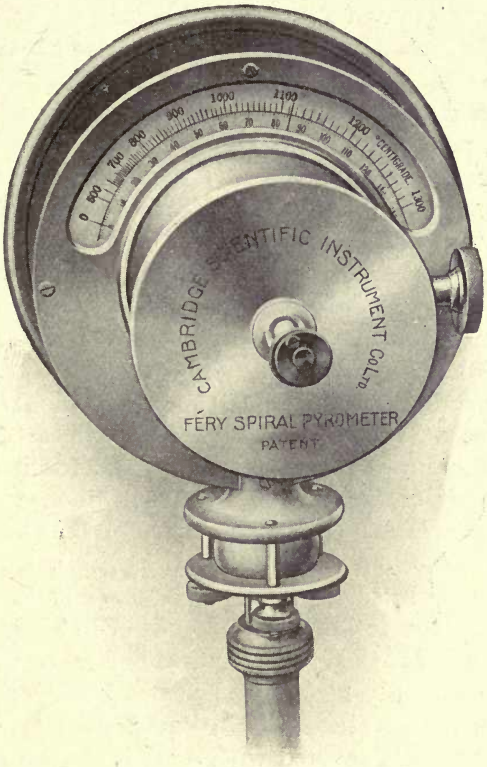


FIG. 42.—Féry spiral pyrometer.

readily seen from Fig. 42, and although not as accurate as the more elaborate type described on p. 70, it is serviceable for many industrial purposes when only a moderate degree of precision is sufficient.

The Féry pyrometer is also made with a lens in place of the reflecting mirror. For industrial purposes the lens is of glass,

which absorbs and reflects a certain amount of the energy and transmits the remainder. The Stefan-Boltzmann law cannot therefore be assumed to hold in this instrument. This law becomes more nearly applicable if the lens is made of fluorite, which for temperatures above 900° C. does not seriously alter the radiations transmitted through it. In either case, however, the instrument may be readily calibrated without particular regard to the laws of radiation by comparison with a standard instrument sighted on the same object.

Radiation pyrometers of the fixed focus type represented by Fig. 37, p. 69, are made by several firms. These differ only in their details from the adjustable focus type and hardly need further description, except perhaps to say that the pyrometer case usually needs to be longer than in the adjustable focus type because the front diaphragm used becomes the source or sighted object.

Radiation pyrometers are usually calibrated for black body radiations and give "black body temperatures." If the sighted object does not fulfil black body conditions the observed temperatures will be below the true temperatures. Black body conditions are practically obtained, for instance, in a closed furnace of *uniform* temperature lined with firebrick and sighted through a comparatively small hole in the furnace, but not in a furnace which is more or less surrounded by a surface at a different temperature (i.e. usually a lower temperature as in a locomotive boiler furnace). It might be mentioned here that the temperature inside a reverberatory furnace is commonly higher by perhaps 100° C. or more than the average temperature of the liquid steel on the hearth, because the steel is covered with a layer of slag which has to conduct the heat and therefore has a gradient of temperature.

When a radiation pyrometer calibrated for black body conditions is sighted on to a body (say, solid or liquid metal) in the open the measured temperature is the apparent black body temperature, which is below the true temperature of the body. For molten iron* or molten copper in the open the readings may be several hundred degrees below the true

* *Characteristics of Radiation Pyrometers*, Burgess and Foote, Bureau of Standards, U.S.A.

temperatures. If the surface of the metal is oxidised, the observed temperatures of the surface of copper oxide may be about 150° C. too low, and with iron oxide 30° C. to 50° C. too low.

Oxide of iron is also a poor conductor of heat, and thus the surface temperature of the oxide in the open is below that of the metal underneath. According to Burgess and Foote the difference may be about 10° C. at 600° C. and about 60° C. at 1000° C. This probably refers to a thin scale of iron oxide as differences of over 100° C. have been noted by other observers between the surface of the oxide and that of the metal at about 1000° C. Although somewhat uncertain, it is seen that the gradient of temperature through the oxide to some extent accentuates the lack of black body conditions of the surface of the oxide sighted in the open.

The Foster Instrument Company give the following values as examples of the necessary corrections for their fixed focus radiation pyrometer when calibrated for black body conditions. These corrections are to be added to a reading of 1000° C.

Surface.	Out in Open.	Recess of depth half its diameter.	Recess of depth one and a half times its diameter.
Crucible Clay .	38° C.	10° C.	2° C.
Iron Oxide . .	51° C.	13° C.	2° C.
Platinum . .	84° C.	21° C.	4° C.

In general the total emissivity E of a substance may be defined as the ratio of the total energy I_1, emitted per unit of surface at a given temperature, to the total energy I emitted by a black body per unit of surface at the same temperature. If τ is the true absolute temperature when the observed temperature by the radiation pyrometer is τ_1, and τ_0 is the receiver temperature,

Then, $I = c(\tau^4 - \tau_0^4)$ approximately
and, $I_1 = c(\tau_1^4 - \tau_0^4)$,,
where c is a constant.

Thus, $$E = \frac{\tau_1^4 - \tau_0^4}{\tau^4 - \tau_0^4}.$$

The τ_0^4 term can generally be neglected.

Thus, $$E=\frac{\tau_1^4}{\tau^4}$$

or, $\tau_1=\sqrt[4]{E}\,\tau$.

Values of the emissivity E are given on p. 158.

To ensure practically black body conditions for observation in a furnace it is best to insert a cast-iron or fireclay tube closed at one end as is shown at A in Fig. 43, and to sight the instrument on to the closed end of the tube as is indicated in the illustration. But if the surfaces of the furnace walls are much

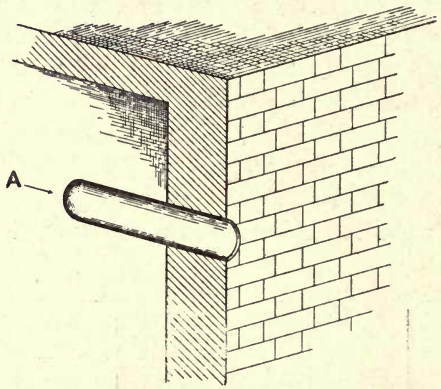


FIG. 43.—Closed tube in furnace for radiation pyrometers.

below the temperature of the gases there is no certainty that the closed tube acquires the temperature of the gases as it may radiate heat to the furnace walls. In any case, the closed tube should be large enough to ensure that the pyrometer is not sighted upon the sides of the tube instead of on the closed end.

Errors of Radiation Pyrometers.—The principal sources of error in radiation pyrometers may be enumerated as follows :

1. The influence of lag, or time required to obtain a constant reading.

2. The effect of distance between the pyrometer and radiator and of the size of image.

3. The effect of dirt or dust on the " optical " system.

4. Lack of "black body conditions" of radiator and receiver and the influence of temperature of receiver.

The Influence of Lag.—On exposing a radiation pyrometer to the radiations from a source at constant temperature, the indications of the pyrometer show a time lag, during which time the instrument is heating up. Eventually a condition of equilibrium is reached when the receiver loses by conduction, convection, and radiation as much heat as it receives. Different pyrometers, even of the same make, seem to exhibit different times of lag, and to keep this time lag small the heat capacity of the receiver should be reduced to a minimum, and also the thermo-couple wires should be of as small a diameter as possible, consistent with mechanical strength, in order to prevent excessive conduction of heat along the wires. The maximum reading of the pyrometer should be obtained in less than one minute after exposure, but in some cases there is a slight decrease in the reading after attaining the maximum, due to conduction along the thermo-couple wires, and due to the receiver losing heat by convection more effectively as the exposure is prolonged. Even then, however, a steady reading should be obtained after a few minutes' exposure. The silvered glass focusing mirrors often used in the Féry type of pyrometer do not form a really satisfactory screen for the excess radiations entering the pyrometer, and it is better to use close-fitting copper mirrors (gold-plated) instead which will effectively conduct most of the heat falling on them to the pyrometer casing and will rapidly attain a steady temperature. In any case it is advisable to use a pyrometer under the same conditions of time exposure as obtained during the calibration of the instrument, and for accurate work requiring rapid measurement of temperature the pyrometer should be tested for the effect of time lag.

The spiral type of Féry radiation pyrometer, and similar mechanical pyrometers, are particularly liable to a large time lag, for not only has the receiving system a comparatively large capacity for heat but the mechanical system is subject to all the errors of elastic lag of the expansion device.

The Effect of Focusing Distance and Size of Image.—It was seen on p. 69 that, from the simple geometrical con-

siderations of the optical systems, the readings of a radiation pyrometer theoretically should be independent of the focusing distance from the pyrometer to the radiator or source, and also independent of the size of the radiator and image, provided the radiator is of sufficient size for the aperture of the instrument. Actually this simple condition is hardly ever fulfilled because of (1) atmospheric absorption, and (2) imperfections of the instrument. The error due to atmospheric absorption is likely to be very small unless fumes or fog intervene between the sighted object and the instrument. The imperfections of the instrument include such factors as the optical aberration of the gold-plated mirror of the Féry pyrometer and the increase of the temperature of the pyrometer by radiation and convection as the instrument is brought nearer the source.

The size of image has an important influence on the accuracy of radiation pyrometers. Referring to the Féry pyrometer described on p. 70, it is obvious that the source should be of sufficient size for its image to cover at least the hole in the limiting diaphragm in front of the receiver. With the usual construction of the Féry pyrometer this limiting diaphragm is the hole at the centre of the inclined focusing mirrors.

The size of the image may be altered by varying the focusing distance, the size of the source remaining constant, or by varying the size of the source with the focusing distance constant. The relation between the diameter of the source or radiator D_s, the diameter of the image D_i, the focusing distance u from mirror to source, and the focal length f of the mirror, is given by the equation,

$$D_i = \frac{D_s}{\left(\frac{u}{f} - 1\right)}$$

Therefore the diameter of the image D_i can be calculated when the other values are known.

Messrs. Burgess and Foote* have experimented on several Féry pyrometers, using various focusing distances and sizes of source. They used a large nickel (oxide) strip heated

* *Characteristics of Radiation Pyrometers*, Bureau of Standards, U.S.A.

electrically, in front of which, at a distance of 1 or 2 cm., were placed blackened water-cooled diaphragms of various sizes of opening from 1·9 cm. to 12 cm., and therefore the diaphragm openings acted as the real sources of radiation. Any one of these diaphragms could be brought in front of the pyrometer, and the pyrometer was arranged to be readily adjustable to any focusing distance from about 80 to 300 cm. Even though the image always more than covered the diaphragm hole in the focusing mirrors the size of the image had an appreciable influence on the pyrometer readings. For example, of three pyrometers, Nos. 1, 2, and 3, calibrated with a diameter of image ·4 cm., the pyrometer readings of e.m.f.'s were too low by 32, 11, and 18% respectively with a ·2 cm. diameter of image, and with a 1·1 cm. diameter image the readings of e.m.f.'s were too high by 17, 2, and 2% respectively. The corresponding percentage errors of absolute temperature are approximately one-quarter of the above values; thus if the correct temperature were 1500° C. with the ·4 cm. image, the corresponding reading with the ·2 cm. image would be 1340° C., 1445° C., and 1410° C. respectively, and with the 1·1 cm. image would be 1580° C., 1510° C., and 1510° C. respectively.

It would be noted particularly that No. 1 pyrometer showed a considerable error with the ·2 cm. image and also with the 1·1 cm. image. The focusing mirrors of this pyrometer, however, were of thin glass silvered on the back surface. No. 2 pyrometer had similar focusing mirrors, but had a metal diaphragm located between the focusing mirrors and the receiver. In No. 3 pyrometer the metal diaphragm was absent, but the focusing mirrors were of gold-plated sheet copper. The errors are due principally to the heating of the focusing mirrors and some of the heat being transmitted by radiation and convection to the receiver from the back of the mirrors. In Nos. 2 and 3 pyrometers, the metal diaphragm in No. 2, and the copper mirrors in No. 3, conducted a large portion of the excess heat energy falling on them to the pyrometer case where it was dissipated.

The Effect of Dirt or Dust.—The ordinary calibration of radiation pyrometers is usually made with the mirrors or lens

quite clean. In industrial practice the condensing mirror of the Féry pyrometer, for instance, is liable to get coated with dirt or dust, and then the instrument may read too low by over 100° C. If necessary the mirror may be detached and carefully washed with water. Mr. Whipple states that a slight film of oxide on the surface of the gold mirror of the Féry pyrometer does not seriously affect the amount of radiation reflected.

Radiator and Pyrometer not fulfilling "Black Body" Conditions.—Examples were given on p. 74 showing the influence of a radiator which does not fulfil black body conditions. Burgess and Foote* state that the selective reflection of gold in the visible spectrum for temperatures up to 2500° C. does not alter the amount of the total energy emitted by the black body and reflected from the gold surface by more than about 2%, which is equivalent to a possible maximum influence (reduction) of the absolute temperature reading at high temperatures of about ½% if the pyrometer were calibrated only at low temperatures. When the pyrometer is sighted upon a black body at temperatures less than 2500° C., approximately 3% of the incident radiant energy on the gold mirror is lost by absorption and dissipated by conduction, convection, and radiation to the outside case. There is an additional loss of 1% or so by reflection from the blackened receiver or thermo-junction disc. At higher temperatures the selective reflection of gold has a greater influence on the amount of radiant energy absorbed; for example, for a black body temperature of 4000° C. the reflection coefficient† is only about ·87. Thus, the Féry radiation pyrometer calibrated at temperatures below 2500° C. could not be safely used to indicate higher temperatures without allowing for the selective reflection of the gold mirror.

Although the inside surface of the pyrometer case is thoroughly blackened to minimise the reflection of stray rays, some reflection does occur, and it is best to have a fine screw thread cut on the inside surface of the case.

The temperature of the receiver and the thermo-junction

* *Characteristics of Radiation Pyrometers*, Bureau of Standards, U.S.A.

† That is, the ratio of the reflected energy to the incident radiant energy.

increases with the amount of energy absorbed, that is, with the temperature of the source. According to Messrs. Burgess and Foote* the temperature of the receiver may be about 200° C. when the pyrometer is sighted on a source at 1500° C. for the average run of Féry pyrometers, though it varies greatly with different pyrometers.

It is sometimes assumed that the Stefan-Boltzmann law, $e \propto (\tau^4 - \tau_0^4)$, applies without modification to radiation pyrometers, where e is the energy absorbed by the receiver, τ the absolute temperature of the source, and τ_0 the absolute temperature of the receiver, and this law is then used to extend the scale of temperatures beyond the calibrated range. Owing to the various instrumental imperfections, however, the law only applies approximately, and instead of the index 4, experiment shows the more general relation is given empirically by,

$$e = a\,(\tau^b - \tau_0^b\,).$$

Thus, $$\log e = \log a + b\left[\log \tau - \frac{\cdot 4343}{b}\left\{\left(\frac{\tau_0}{\tau}\right)^b + \ \ldots\right\}\right]$$

If $$\frac{-\cdot 4343}{b}\left(\frac{\tau_0}{\tau}\right)^b = q,$$

Then, $$\log e = \log a + b\,(\log \tau + q) \text{ nearly.}$$

Since the quantity q is only small and b is not far from the value 4 it may be assumed that,

$$q = -\frac{\cdot 4343}{4}\left(\frac{\tau_0}{\tau}\right)^4.$$

Therefore, to find the value of b from a set of experimental observations, the logarithm of e and $(\log \tau + q)$ are plotted on graph paper, when b is given by the gradient of the line.

Messrs. Burgess and Foote have experimentally determined b for many radiation pyrometers. With 22 different Féry pyrometers b had values ranging from 3·28 to 4·26, the average for the 22 instruments being about 3·89.

The properties of thermo-junctions, galvanometers, and potentiometers were discussed in Chapter III, and hardly need further reference here, except perhaps to say that the potentiometer method of measuring the e.m.f. is generally

* *Characteristics of Radiation Pyrometers*, Bureau of Standards, U.S.A.

more accurate than the galvanometer method, though the latter is more commonly used in ordinary practice on account of its general convenience.

Optical Pyrometers.—Instead of using the total radiations, optical pyrometers are arranged to make use of the luminous radiations only. In the usual construction of this type of instrument the intensity of the light radiated from the sighted object is compared or matched with that from some standard source, and the main difference between the various instruments lies in the methods by which the comparison is made. The laws of radiation are discussed in *Heat Transmission by Radiation, Conduction, and Convection*, and a knowledge of these laws will be assumed in the following descriptions.

It is not the usual practice to attempt to measure the intensity of the whole of the luminous radiations for the reason that the sensitiveness of the eyes varies for different persons viewing full luminous radiations, and therefore it is found to be more accurate to compare the radiations of some definite wave-length, that is, monochromatic light. Perhaps it is desirable to mention here that the intensity of the radiations is not the same for all substances at a particular temperature unless the substances are surrounded by an enclosure at the same temperature. For example, in the open the intensity of light from incandescent iron or from carbon is much greater than from porcelain or from platinum at the same temperature. The temperatures indicated by an instrument calibrated under black body conditions are known as "black body temperatures," and therefore when the instrument is sighted on a body which is in the open and does not fulfil black body conditions the apparent temperature will be lower than the true temperature ; but provided the surface does not alter in character there will be nearly a constant relation between them. For example, the recorded black body temperature of a piece of exposed iron at 1200° C. (2192° F.) will be about 1140° C. (2084° F.) and that of porcelain at the same temperature about 1100° C. (2012° F.)*, when comparing the red light emitted. This means that iron and porcelain at 1200° C. emit red light of the same intensity as that emitted by a black body

* *The Measurement of High Temperatures*, Burgess and Le Chatelier.

at 1140° C. and 1100° C. respectively. Therefore, to ascertain the true temperatures of such bodies it is necessary to know the relations between the apparent and the true temperatures by direct experiment under the particular conditions in which the hot body is exposed. If there should happen to be large differences of temperature in the neighbourhood of the sighted body reflection from the surface of the object may also affect the apparent temperature. Under certain conditions some substances are luminescent; for instance, the ordinary gas mantle which has been saturated with thorium salts becomes luminescent at high temperatures. For such cases the ordinary laws of radiation do not apply.

Le Chatelier in 1892 seems to have been the first experi-

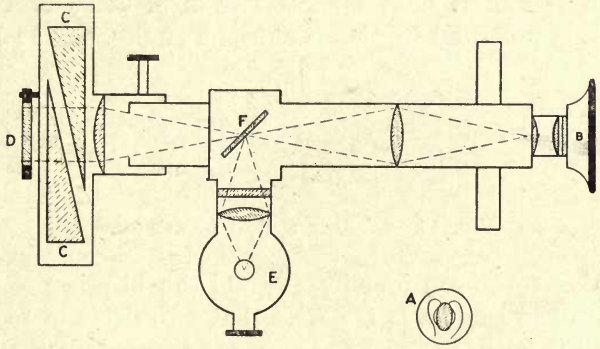


Fig. 44.—Féry optical pyrometer.

menter to design and use an optical pyrometer successfully. An expanding or iris diaphragm was used to alter the amount of light entering the instrument. In this case the intensity of the light would vary as the square of the diameter of opening and a calibration at two known temperatures was sufficient to connect the temperatures with the diameter of the opening of the diaphragm. A modification of the Le Chatelier instrument was introduced by Féry, represented in Fig. 44, where a pair of glass absorbing wedges C were placed in front of the objective of the telescope and could be moved laterally by means of a screw until the light from the object under observation was made photometrically equal to that emitted by the standard lamp. These pyrometers, however, are not now con-

sidered to be as accurate or as convenient as other instruments more recently developed.

Wanner Pyrometer.—In this instrument the monochromatic rays of light from the object and from the standard lamp are produced spectroscopically and are therefore truly monochromatic. The comparison of the brightness is obtained by means of a polarising device. The arrangement is represented diagrammatically in Fig. 45. Diffused light from a standard 4-volt electric lamp passes through the slit S_1 and from the object through the slit S_2. The two beams are rendered parallel by the lens L_1, which is placed at a distance equal to its focal length from the slits, and are then each dispersed into a continuous spectrum by the direct-vision prism P. The polarising prism R next separates each of these beams into two beams polarised in planes at right angles.* The lens L_2

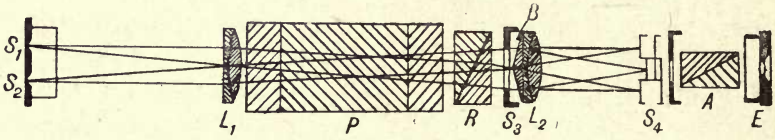


FIG. 45.—Wanner optical pyrometer.

would therefore form four images and the bi-prism B in contact with the lens L_2 is made so that two fields of red light, polarised in planes at right angles, are focused on the slit S_4, one coming from the slit S_1 and the other from S_2. All the other images are cut off at the slit S_4. These two beams of red light enter the Nicol analyser† A and the observer looks through the eyepiece E to ascertain when the two beams are of equal intensity. This can be obtained by rotating the analyser A, and the angular position of the analyser is then a measure of the temperature of the object. If the intensities of

* Various substances are capable of polarising the light passing through them, i.e. instead of the issuing light consisting of waves in all directions, two beams are produced, each consisting of waves only in a single plane, and the two planes are at right angles.

† The analyser is simply another polarising prism. In a particular angular position of the analyser, polarised light would be cut off completely; in another position at right angles to this the maximum amount would pass through. For an intermediate angular position only a component of the polarised light could pass through. For a complete description of polarisers reference should be made to any standard textbook on "Light."

the light from S_1 and S_2 were equal, and the analyser set at an angle of 45° with the plane of polarisation of each beam, the eye would see a single circular red field of uniform brightness. If one slit then received more light than the other the corresponding field would brighten, but the two fields could be brought back to equality again by rotating the analyser in the proper direction, thereby cutting off more light from the brighter field and admitting more from the darker. The angle of rotation of the analyser indicates the temperature of the object to some scale. Thus, if θ is the angle turned through to bring the two fields to equal brightness, and I_1 and I_2 the intensities of the light through S_1 and S_2,

then,
$$\frac{I_1}{I_2}=\tan^2\theta.$$

For calibration purposes a standard amyl-acetate lamp is provided on which the instrument can be sighted and the current passing through the electric lamp is adjusted so that equal brightness is obtained from the two lamps with the analyser set at the "normal" or "zero" point. The height of the flame needs to be carefully adjusted to the gauge provided and should burn about ten minutes before readings are taken.

If I_0 represents the intensity of the light from the standard amyl-acetate lamp, τ_0 the corresponding equivalent absolute temperature, and θ_0 the reading in degrees on the scale of the analyser for the "normal" or "zero" position, and I, τ, and θ are the corresponding values when sighting upon the object whose temperature is required,

then,
$$\frac{I_0}{I}=\frac{\tan^2\theta_0}{\tan^2\theta}$$

Also Wien's law gives,

$$\log\frac{I_0}{I}=\frac{\beta_1}{\lambda}\left(\frac{1}{\tau}-\frac{1}{\tau_0}\right)$$

$$\therefore \quad 2\log\frac{\tan\theta_0}{\tan\theta}=\frac{\beta_1}{\lambda}\left(\frac{1}{\tau}-\frac{1}{\tau_0}\right)$$

or generally,

$$\log\tan\theta=a+\frac{b}{\tau}$$

If τ and τ_0 are absolute temperatures in degrees Cent. the constant $\beta_1 = 14{,}500$ for a black body, and the wave length $\lambda = 0{\cdot}656\mu$ usually, where μ signifies 0·001 mm., i.e. $\frac{\beta_1}{\lambda} = \frac{14{,}500}{0{\cdot}656}$.

The apparent temperature τ_0 of the standard lamp may be taken at 1673° C. absolute, and thus the apparent black body temperature τ of the sighted object is calculable from the above equations. In the latest forms of this instrument the standardisation has been further simplified and made direct reading by having a second scale on the analyser graduated in temperatures.

For work of precision a rheostat and milliammeter should be inserted in series with the battery and electric lamp so that the current through the lamp can be maintained constant. Otherwise the slightly changing voltage of the battery with the period of operation may affect the accuracy of the results.

A disadvantage of this type of instrument is the difficulty of sighting the instrument exactly on the spot desired. Also the absorption of light which takes place through the large number of prisms and lenses renders it useless for temperatures below about 900° C. (1652° F.).

The Cambridge Scientific Instrument Company manufacture an optical pyrometer constructed on similar principles to the Wanner pyrometer, and have taken special precautions in their design to protect the optical system against dust.

Instruments using polarising apparatus are liable to error if the object sighted on emits polarised light. When an incandescent object is viewed at right angles to its surface the amount of polarised light is small, but when viewed at an acute angle the amount of polarised light in this direction may be appreciable. In general, the plane of polarisation of this light would probably be different from the plane given by the polariser in the instrument, with the result that the polariser would naturally eliminate more or less of the polarised light emitted by the object and the intensity of the light in the image would be affected thereby, rendering an accurate estimation of temperature impossible. This source of error can be eliminated by taking the mean of four readings for

azimuths 90° apart. For many substances, however, such as iron and porcelain, the emission of polarised light is practically negligible.

Holborn-Kurlbaum Pyrometer.—This instrument is represented diagrammatically in Fig. 46. A small 4-volt incandescent lamp L with a horseshoe filament, as shown in the sectional view, is mounted so as to lie in the focal plane of the objective and of the eyepiece. Suitable stops D, D, D, are provided and a focusing screw S for the objective is used to bring the focus

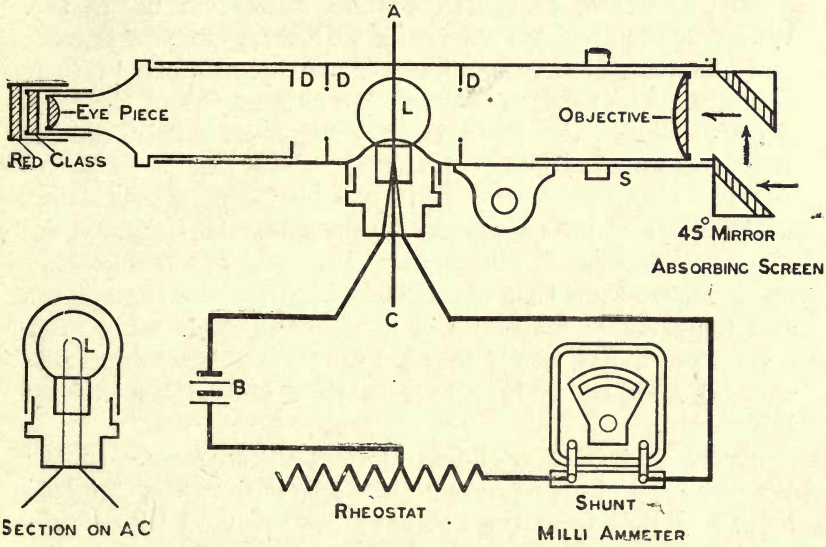


FIG. 46.—Holborn-Kurlbaum optical pyrometer.

in the plane of the filament. The lamp circuit is completed through a two-cell storage battery, a rheostat, and a milliammeter.

The telescope is focused on the sighted object so that the image of the object is in the plane AC, and the current through the lamp is adjusted by means of the rheostat until the tip of the lamp filament just disappears against the bright background. A previous calibration of the lamp connects the current and apparent temperature of the filament, and thus the temperature of the object is deduced from that of the filament.

At high temperatures the brightness of the image may be too intense for the observer's eyes, but the introduction of monochromatic red glasses before the eyepiece enables readings to be obtained. Below about 800° C. (1472° F.) the red glasses are not necessary, that is, down to the limit of the instrument, say, 600° C. (1112° F.). Two red glasses are usually required for temperatures above 1200° C. (2192° F.), and above 1500° C. (2732° F.) it is usually necessary either to put in absorbing glasses or the double-prism mirror shown in Fig. 46 before the objective, which, of course, require calibration before use. With care the precision obtainable with this pyrometer is good, and different observers do not differ appreciably in their readings. The relation between the current C and the temperature T for the lamp is in general accurately enough expressed by a formula of the type,

$$C = a + bT + cT^2$$

where a, b, and c are constants for the particular lamp. If the lamp has been aged or burned for some time at a temperature much higher than that obtained in ordinary use the current and temperature relation will not change appreciably after several years' use, but if not aged in this manner considerable changes may result in course of time and errors thereby introduced.

Errors and Corrections in Optical Pyrometers.—In the Wanner type of instrument both the light from the standard lamp and that from the hot body are analysed by spectroscopic means, and a practically monochromatic band in the red is selected for comparison. In the other types the red light is obtained by means of red absorption glasses, and one objection to these glasses is that the light is not truly monochromatic. With the best types of red glass the wave-lengths transmitted may vary from $0{\cdot}6\mu$ to $0{\cdot}7\mu$ with a maximum intensity somewhere between these values, and dependent to some extent upon the temperature of the source, as is signified by the relation $\lambda_m T = \text{constant}$. The hot body, however, is not a constant temperature, whereas that of the standard source in some types of instrument is practically constant. This introduces small variations and affects the adjustment of the two fields of light to equality. The error involved

may be of the order $\pm 10°$ C. at 1500° C. if not allowed for in the calibration of the instrument.

The adjustment of the current through the standard lamp, usually an electric filament, is commonly obtained by means of a rheostat. The steps in the rheostat should not introduce changes in the temperature by more than 5° C. at each step, as obviously the accuracy of the comparison is practically limited to the change of temperature at each step.

Optical pyrometers of the types described have come into extended use in steel works in recent years for measuring furnace temperatures, the pouring temperatures of liquid steel, and steel temperatures during re-heating, forging, rolling, and annealing. Their chief merit lies in the absence of time lag, the ease with which they can be operated, and the knowledge available of the emissivities of iron and iron oxide for the wave-lengths used, but they are subject to errors or corrections according to the conditions under which they are used. Being calibrated for black body conditions, the optical pyrometer sighted into a furnace of *uniform* temperature should give the true temperature. The temperature of a furnace, however, is rarely quite uniform, and some reflection may occur from a body of metal at a lower temperature than the walls or flames. In that case also radiations are emitted by the flames coming between the metal sighted on and the instrument. With the open hearth furnace the temperature of the molten steel on the hearth may be much below that of the furnace itself, because the heat has to travel through the layer of slag on the top of the metal. To obtain the temperature of the steel before pouring it seems best to sight the pyrometer on to the bottom of a refractory tube well immersed in the steel.

As in the radiation pyrometers, when the optical pyrometer is sighted on a body in the open the conditions may be far removed from the black body conditions for which the instrument is calibrated. When estimating the temperature of steel in the open the problem is further complicated by the coating of oxide which may be formed on the surface, the oxide having a higher emissivity than the metal; but the oxide is a poor conductor of heat and therefore the surface

of the oxide during cooling in the open is at a lower temperature than the metal underneath.

The error involved due to divergence from black body conditions may be estimated if the emissivity of the surface is known by making use of Wien's law,

$$\log_e \frac{I_0}{I} = \frac{\beta_1}{\lambda}\left(\frac{1}{\tau} - \frac{1}{\tau_0}\right)$$

If $I_0 = EI$ is the intensity of the light of wave length λ emitted when the apparent temperature is τ_0, the relative emissivity of the surface being E, and I is the intensity emitted by a black body at the true temperature τ, then,

$$\log_e E = \frac{\beta_1}{\lambda}\left(\frac{1}{\tau} - \frac{1}{\tau_0}\right)$$

If λ is the wave-length expressed in terms of the unit μ,* $\beta_1 = 14{,}500$. Thus taking $E = 0{\cdot}4$ for molten steel with a clean surface, and $\tau_0 = 1773°$ C. absolute (1500° C.), then for $\lambda = {\cdot}67\mu$,

$$-{\cdot}9163 = \frac{14500}{{\cdot}67}\left(\frac{1}{\tau} - \frac{1}{1773}\right)$$

or, $\tau = 1918°$ C. abs. or, 1645° C.

The true temperature is thus 145° C. above the apparent temperature given by the optical pyrometer for these conditions.

As mentioned on p. 86, with the polarising type of pyrometer the pyrometer should be sighted as nearly normal to the surface as possible, because the light emitted at an acute angle to the surface may be polarised to some extent. Therefore in sighting on to a stream of molten steel issuing from a furnace the centre of the stream should be chosen rather than the edges viewed from the pyrometer. Fumes between the metal and the pyrometer, by absorbing light, would cause a low reading, and therefore if possible it is best to observe the metal from the windward side. With ordinary diffused lighting reflection from the surface of the metal does not affect the accuracy of the reading to any appreciable extent,

* μ represents a wave length of $\frac{1}{1000}$ millimetre.

but care should be taken to avoid direct reflected light from the surface of the metal.

The effect of the oxide film on the surface of an ingot is discussed in connection with radiation pyrometers on p. 75, and further reference is hardly necessary.

CHAPTER V

VARIOUS OTHER PYROMETERS

Calorimetric Pyrometers.—This method was one of the earliest in use for the estimation of high temperatures. A suitable small piece of metal is subjected to the temperature it is desired to measure and when uniformly heated is rapidly transferred into a vessel of water well insulated to prevent loss of heat externally. From the known weight and specific heat of the metal and the known weight of water and the water equivalent of the apparatus, together with the rise of temperature of the water, a simple calculation gives an estimate of the initial temperature of the piece of metal.

Thus, if m=weight of metal heated.

s=mean specific heat of metal.

T=temperature of metal before immersion.

t_1=initial temperature of water in calorimeter.

t_2=final ,, ,, ,, ,,

W=weight of water in calorimeter.

w=water equivalent of calorimeter.

Then, Heat lost by metal=Heat gained by water.

Or, $ms\ (T-t_2)=(W+w)\ (t_2-t_1)$.

Or, $$T=\frac{(W+w)\ (t_2-t_1)}{ms}+t_2.$$

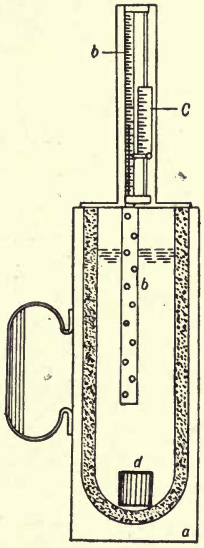
In practice it is necessary to take great precautions to ensure a reasonable degree of accuracy by this method. One difficulty is to obtain a metal which does not oxidise at high temperatures. Platinum is too dear for the purpose. Iron and copper oxidise on immersion and the oxidised surface peels off. Nickel has been found to be fairly suitable if not heated beyond 1000° C. (1832° F.). Another difficulty is the specific heat of the metal, which usually varies with the

temperature, and an exact determination is hardly ever obtainable. Also there is nearly always a loss of heat and an unknown fall of temperature of the heated metal during its transference to the calorimeter. Notwithstanding the liability of such instruments to considerable errors when used carelessly they are of some service for an approximate estimate of temperatures, say to within 20° or 30° F. at 1500° F., when only an occasional determination is required, or where the importance of the measurements would not justify the installation of the more elaborate and more expensive pyrometers previously described.

The following values may be taken to represent the total heat in one pound of nickel measured from 0° C. (32° F.).

HEAT IN 1 LB. NICKEL FROM 0° C. OR 32° F.

Temperature.		B.Th.U. per pound.
°C.	°F.	
0	32	0
100	212	20·7
200	392	41·9
300	572	71·1
400	752	91·8
500	932	116
600	1112	138
700	1292	164
800	1472	189
900	1652	216
1000	1832	245



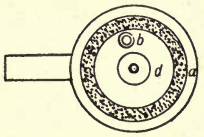


FIG. 47.—Siemens' calorimetric pyrometer.

An industrial form of the calorimetric pyrometer made by Siemens Bros. and Co., Ltd., is illustrated by the sectional view in Fig. 47. It consists of a double copper cylinder, the inner portion containing water and insulated from the outer with felt to prevent the external loss of heat. This double cylinder is enclosed in an outer copper cylinder *a* with an air space. The thermometer at *b* is protected from damage by a perforated brass tube, and near the stem of the thermometer is placed a sliding piece *c* carrying a pointer, and on *c* a temper-

ature scale is marked. In using the instrument the specified quantity of water is placed in the calorimeter and the pointer on *c* is brought opposite the top of the mercury column in the thermometer. The metal cylinder is heated in a crucible or special muffle until it is certain to have acquired the proper temperature to be measured and is then rapidly withdrawn and dropped into the water. After shaking the instrument to ensure a uniform temperature in the water the column of mercury is watched, and on attaining its highest position the reading given on the scale *c*, added to the initial reading of the thermometer, denotes the temperature of the hot metal. If the instrument has been calibrated against the more accurate platinum resistance or the thermo-electric pyrometers under definite conditions of manipulation a fair degree of accuracy is attainable.

Messrs. Siemens Bros. and Co. suggest the following metals as suitable within the specified ranges :—

For temperatures up to 1800° F. or 1000° C.—Copper or Iron.
,, ,, ,, 2200° F. or 1200° C.—Nickel.
,, ,, ,, 2700° F. or 1500° C.—Platinum.

The original weights of these metal cylinders supplied with the instrument are : Copper, 137 grms. ; Wrought Iron, 112 grms. ; Nickel, 117 grms.

As mentioned previously, in course of time the copper and iron cylinders lose weight by scaling. The makers supply tables of factors for these metals by which the readings on the sliding scale *c* are multiplied according to the weight of the cylinder.

Expansion and Contraction Pyrometers.—About 1782, Wedgwood, the famous potter, introduced his contraction pyrometer for the arbitrary estimation of the temperatures in his kilns or furnaces. His method consisted in the measurement of the contraction of small cylinders made from special clay after having been subjected to the temperature. His measuring device was a tapered groove, and each inch of length was divided into twenty equal parts, making 240 divisions altogether ; each division was called one degree. The width of the groove at the zero mark was 0·5 inch and at the 240 mark was 0·3 inch.

This apparatus is still used in pottery kilns and furnaces, and various attempts have been made to deduce the connection between the Wedgwood scale and the ordinary scales of temperature, but it has been found that different mixtures of clays are so variable in the amount of contraction obtained as to render a strict comparison impossible.

In recent years the Wedgwood pyrometer has been improved both in the materials and in the form of the test-piece. In 1900 Watkin introduced discs of clay with a hole in the centre so as to facilitate withdrawal from the furnace or kiln. The diameter of the disc is measured to a thousandth of an inch in a manner similar to that of Wedgwood.

Buller's trial rings of clay are of similar form and measure $2\frac{1}{2}$ in. in diameter. The contraction of the ring during the different stages of firing is measured on a special gauge made by Messrs. Keeling and Walker, Stoke-on-Trent.

The relative expansion of two substances was one of the earliest of methods used in estimating temperatures. A common form, indicating the temperature on a dial, consists of a tube of iron enclosing a rod of graphite. Their differential expansion with change of temperature operates, by means of multiplying levers, a pointer moving over a dial graduated in degrees. The coefficient of expansion of most materials, however, is liable to change with time under prolonged or repeated heating, and frequent calibration is necessary. Also varying depths of immersion sometimes affect the readings. About 800° C. (1472° F.) is the useful limit of the above instrument, and it can only be trusted for rough estimations of temperature.

The Joly "Meldometer" has been used to determine melting-point temperatures of metals and salts. It consists of a thin platinum strip supported under a slight tension between two points on levers, and the strip can be heated by an electric current. The change of length of the platinum strip with changes of temperature is measured by micrometer screws. A previous calibration gives an estimate of the temperature of the strip from the measured change of length. In determining the melting-point of a metal or of a salt a speck of the specimen is placed in the middle of the strip under the view of a low-power microscope. The current is increased gradually,

and at the instant of melting, as observed through the microscope, the micrometer is set and read. This instrument is not of much service for industrial work.

Fusion Pyrometers.—When the fusing or melting-point of a metal, alloy, or salt is known, use may be made of this to indicate approximately the attainment of particular temperatures in a furnace. By selecting a number of solids with suitable melting or fusing points and inserting these in the furnace in a suitable manner a rough estimate of the furnace temperature may be obtained, since the temperature may be taken to be equal to or higher than the point of fusion of a substance which fuses in the furnace and lower than that of a substance maintaining its original shape at that temperature.

Messrs. Vogt and Light, of Paris, were the first to use cones made of suitable mixtures of china clay, felspar, lime, etc., with progressive fusing temperatures. Seger, in 1886, after experiments made at the Royal Pottery Works in Berlin, published the results of his investigations on the use of silicates of progressive melting points for the estimation of furnace temperatures. The shape of the "cones" is that of triangular pyramids of 15 mm. side and 50 mm. high. When softening begins under the action of heat the tip of the pyramid manifests an alteration of form and finally the pyramid collapses completely. By varying the composition Seger was able to supply cones having melting points ranging from 590° C. (1094° F.) to 1890° C. (3434° F.) in sixty steps, some of these at intervals of 20° C., others at 30° C. intervals. Each pyramid is stamped with a distinguishing number corresponding to a definite fusing temperature. When estimating a furnace temperature, or when it is desired to ascertain the attainment of a particular temperature in the furnace or kiln, several pyramids are selected having melting points known to be near the temperature to be measured, and these are inserted in the furnace on a slab of refractory material. Inspection at a special sight hole closed with darkened glass enables the furnace attendant to see the cones, and these indicate to him the attainment of a particular temperature corresponding to or near to the fusion point of the cone which last fuses. These

cones are now made at the Central School of Pottery, Stoke-on-Trent.

Various modifications of these cones have been introduced in recent years. Messrs. Holdcroft and Co. produce bars instead of cones, supported at their two ends on a suitable refractory case. At the fusion point the bar sags in the middle, and a series of four of these bars, having progressive fusion points, are usually accommodated on the refractory case.

" Sentinel " pyrometers possessing definite fusion points have been introduced in metallurgical operations by Brearley, of Sheffield. They are used in a similar manner to the Seger cones. The fusion points of metal alloys of definite composition have been used by various experimenters for the estimation of furnace temperatures. They have also been used to indicate the temperature of boiler plates and tubes by embedding plugs of the fusible alloys in the metal of the plates. This method, however, when compared with the more modern methods available for measuring plate temperatures, is considered unreliable.

CHAPTER VI

CALIBRATION OF THERMOMETERS AND PYROMETERS

THE calibration of mercury thermometers was discussed to some extent on pages 9, 10, and 18, and it is now proposed to direct attention more particularly to the standardisation or calibration of thermometers above the boiling point of water (212° F.). For this purpose use may be made of the known boiling or melting points of various substances ; a list of those most suitable is given in Tables II and III, pp. 157, 158.

Sulphur Boiling Point.—Callendar and Griffiths give the boiling point of sulphur at 760 mm. of mercury as 444·5° C. (832° F.) on the constant pressure scale of the gas thermometer. The variation with small changes of atmospheric pressure is given in Table II, p. 157. This boiling point was determined with great accuracy and is generally suitable for calibration purposes, since sulphur boils smoothly without bumping when in a properly arranged apparatus, and commercial sulphur gives the same boiling point as the purest obtainable. This point is generally used for the determination of δ in equation (4) on p. 25, in connection with the platinum resistance thermometer, and if this temperature were not ascertained with a high degree of accuracy an appreciable error would be involved in the measurement of high temperatures when making use of this formula.

A convenient arrangement of the sulphur boiling point apparatus is shown in Fig. 48. A hard glass tube containing a suitable amount of sulphur is first passed through the hole at the bottom of the sheet metal cylinder, which is then packed with magnesia or similar insulating material. The thermometer is inserted into the tube and well clear from the surface of the sulphur. In order to shield

the thermometer bulb from radiations and to prevent drops of the liquid sulphur running down the stem on to the bulb it is advisable to use a screen of sheet aluminium, shown in detail in the side sketch. The end of the tube could be heated gently by a Bunsen burner, or better still the burner could be allowed to play on a cast-iron shield as shown in Fig. 48, which would ensure a more uniform heating of the tube and render it less liable to breakage. By careful manipulation it is not difficult to keep the sulphur boiling so that little or none of the vapour leaves the tube, but giving a definite line of demarcation on the tube, above which would be seen crystals of sulphur, and below this would be condensed vapour running back into the boiling sulphur.

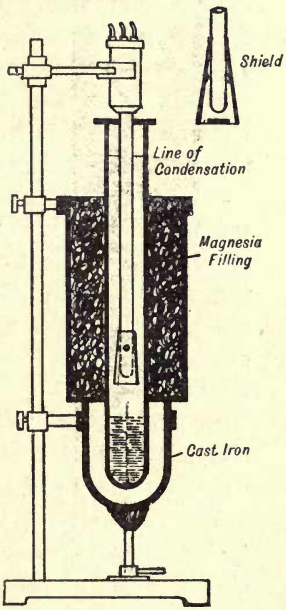


FIG. 48.—Sulphur boiling point apparatus.

The boiling points of naphthalene and benzophenone may be obtained in similar apparatus. Naphthalene is readily obtained of sufficient purity and should have a freezing point of 80° C. (176° F.). Benzophenone is relatively expensive and somewhat difficult to obtain in the pure state. The boiling point of aniline can also be ascertained in a similar manner if a suitable condenser or flask is attached for the reception and condensation of the issuing vapour.

It is sometimes desirable to calibrate a thermometer or pyrometer at higher temperatures than the boiling point of sulphur, and recourse is then usually had to the freezing or melting point of a suitable metal or a salt of definite composition. Such methods are well adapted to the calibration or standardisation of thermo-junctions, and these are usually immersed in the melted metal or salt in a crucible. Readings of the electromotive force would be obtained as cooling took place, and the point of solidification is recognised by the fact that the metal remains at nearly a constant temperature during

the process of solidification. The table III on p. 158 contains the melting or freezing points of the metals most commonly used for calibration purposes. The melting or freezing points of silver and copper should be obtained in a reducing atmosphere. This may be obtained by using a graphite crucible and covering the metal with powdered graphite and a graphite crucible lid. If these metals are exposed to the atmosphere when in the melted condition they readily oxidise, and this lowers the melting point appreciably.

The crucible containing the metal should be deep enough to give sufficient immersion of the pyrometer under test. On cooling down some metals have a tendency to under-cool, that is to remain liquid at temperatures a few degrees below the actual freezing point, but on solidification taking place the temperature rises to practically the same point as when under-cooling is absent. Under-cooling may be almost eliminated in most cases by frequent stirring by means of the pyrometer itself. The under-cooling effect is generally more marked the higher the temperature to which the metal is raised above its freezing point and the more rapid the rate of cooling.

Special electrically heated furnaces have been designed for the melting of metals at high temperatures, and these are usually capable of close regulation.

For a small fee the institutions mentioned on p. 18 will test a thermometer or a pyrometer and furnish a certificate showing the corrections to be applied at various readings of the thermometer.

Calibration of Radiation and Optical Pyrometers.—Two methods of calibration may be used : (1) Direct calibration, where the pyrometer is sighted on a black body at a known temperature, and (2) secondary calibration, where the pyrometer is sighted on the same source as a standardised one of the same type.

The direct method of calibration is generally used for standardisation purposes. It is well known that there is no known material which strictly conforms to " black body " conditions, but it can be shown that a hollow opaque enclosure at a uniform temperature is equivalent to a black body, and

the radiations issuing from a small hole in such an enclosure are black body radiations. One form of black body adopted by the U.S.A. Bureau of Standards is shown in Fig. 49. A solid graphite cylinder D, 16 by 8 cm., is turned in a lathe into the form of a crucible with three diaphragms. This is mounted in an electrical resistance furnace, the back wall of the graphite cylinder being placed 40 cm. from the front opening of the furnace. The temperature of the black body is measured by two calibrated thermo-couples (Pt, 10 Rh–90 Pt), protected by glazed porcelain tubes inserted into the back wall of the graphite cylinder and projecting 1 or 2 cm. into the interior. The back of the furnace is closed by a kaolin diaphragm,

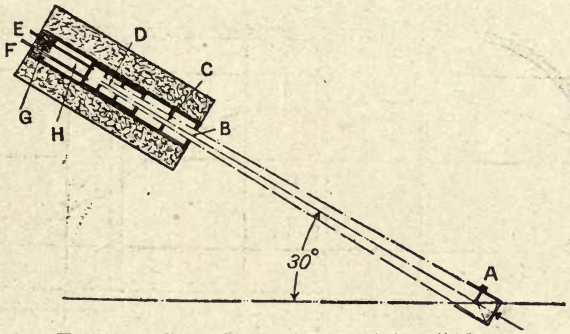


FIG. 49.—Graphite enclosure giving "black body" radiations.

2 or 3 cm. of powdered Marquardt (G) and a plug of asbestos wool. In front of the graphite cylinder are located two or more kaolin or porcelain diaphragms which assist in preventing circulation of air. The furnace tube is of porcelain wound with platinum tape 5 cm. wide, and an auxiliary coil 15 cm. long wound with 1 cm. platinum tape is placed at the front part of the furnace to improve the distribution of temperature. If the pyrometer to be calibrated is of the focusing type it is placed at any convenient standard distance, A, and usually focused on the opening of the inmost diaphragm, which is made of sufficient diameter so that its image just covers the receiver. The sizes of all the other diaphragms are then determined geometrically by drawing the cone of rays to the

pyrometer as shown in the figure. It is found that the variations of temperature which sometimes occur are not greater than 5° C. at 1300° C. over a 10 cm. length of the graphite cylinder.

Graphite usually contains impurities in small quantities sufficient to corrode the furnace and contaminate the thermo-couples after prolonged use, and the graphite also oxidises and crumbles away. The oxidisation of the graphite may be reduced by supplying a stream of nitrogen at the mouth of the tube.

Instead of graphite a black body of Marquardt porcelain has been used similarly arranged, with the closed end hemispherical. The thermo-couples are threaded through small

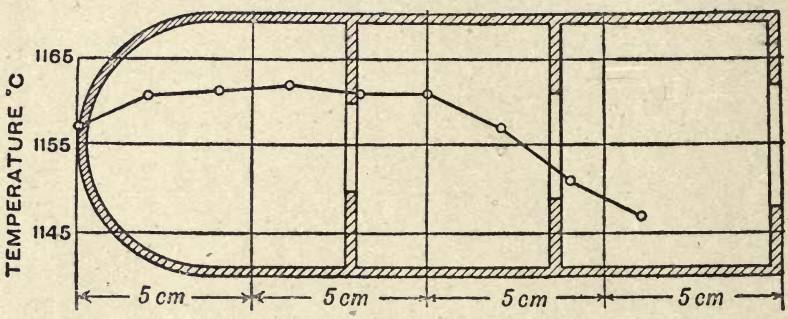


Fig. 50.—Porcelain enclosure giving "black body" radiations.

holes in the closed end.* Fig. 50 illustrates such a porcelain radiator, and a graph is shown of the distribution of temperature when enclosed in the furnace previously described. For a distance of 12 cm. the variation from 1160° C. is in no place greater than 3° C. By the use of such a black body the radiation pyrometer may be calibrated directly from 500° C. to 1500° C. from the readings of the Pt, Rh thermo-junction. Therefore up to this temperature the laws of radiation can be verified for radiation or optical pyrometers and for the measurement of higher temperatures it is assumed that the laws continue to hold. A uniformly heated muffle may be used as a source of radiation up to the fusing point of the brickwork for approximate calibrations.

* *Characteristics of Radiation Pyrometers*, Bureau of Standards, U.S.A.

Calibration by Comparison with Standardised Pyrometer. —The electric furnace and black body of the type discussed, while suitable for standardisation purposes, requires several hours to attain steady temperature conditions and therefore is not generally convenient for ordinary calibration purposes. The pyrometer to be tested may be compared with a standardised one of the same type by sighting upon a radiator at a uniform temperature, even if the radiator or source is not emitting black body radiations. The U.S.A. Bureau of Standards have satisfactorily used an electrically heated sheet of nickel (oxide) for this purpose. A uniform coat of nickel oxide (NiO) forms on the surface of the nickel thus heated to high temperatures, and may be used almost up to 1300° C. It is found that rapid changes of temperature can be made from 500° C. to 1300° C., but it is necessary to cool gradually from 500° C. to the room temperature or flaking of the oxide scale will occur. The strip of nickel used by the Bureau is about 17 cm. long, 13 cm. wide, and ·015 cm. thick, mounted vertically between cooled brass-clamp terminals. It is found that such a strip heated electrically furnishes a source of 12 cm. diameter which is uniform in temperature to within 2° C. at 1200° C. In using such a radiator it is essential that the pyrometer under test and the standardised pyrometer used for comparison should be of the same type so that the departure from black body conditions will affect each pyrometer equally ; otherwise by this method of calibration relatively large errors would be possible if different types of pyrometers were used for the purpose.

CHAPTER VII

THE MEAN TEMPERATURE OF A METAL WALL

THE best arrangement for measuring the mean temperature of a metal wall depends somewhat upon the thickness and general accessibility of the wall and upon the degree of accuracy required. While it is generally convenient, for example, to find the mean temperature of a steam engine or a gas engine cylinder by means of mercury thermometers placed in drilled holes in the metal, such an arrangement would hardly be possible for an engine piston or for the thin wall of a condenser tube.

It is well known that there are practically no cyclical changes of temperature in the wall of a steam engine or gas engine cylinder at a depth of $\frac{3}{8}$ in. or so from the working surface under ordinary conditions of operation. Therefore it follows that a small-diameter mercury thermometer placed in a drilled hole in the metal at this distance from the surface would give the mean temperature at such a point, provided the hole was only slightly larger than the thermometer, and that a little mercury was inserted to increase the thermal contact between the thermometer and the metal and to reduce the tendency of the hole to disturb the flow of heat through the metal. An approximate estimate may sometimes be obtained by binding a thermometer with its bulb in contact with the cylinder wall, surrounding the bulb with non-conducting material on the outside. This method, however, is somewhat crude and is liable to large and uncertain errors.

The late Mr. Bryan Donkin appears to have been the first experimenter to use mercury thermometers in drilled holes

for the measurement of cylinder wall temperatures.* Some of his experiments were conducted on a small steam engine; others on small thick cylinders of various materials but without piston, a small piston valve being operated by an engine so as to admit, cut off, and liberate steam from the experimental cylinder. Others again were made on short thick cylinders of

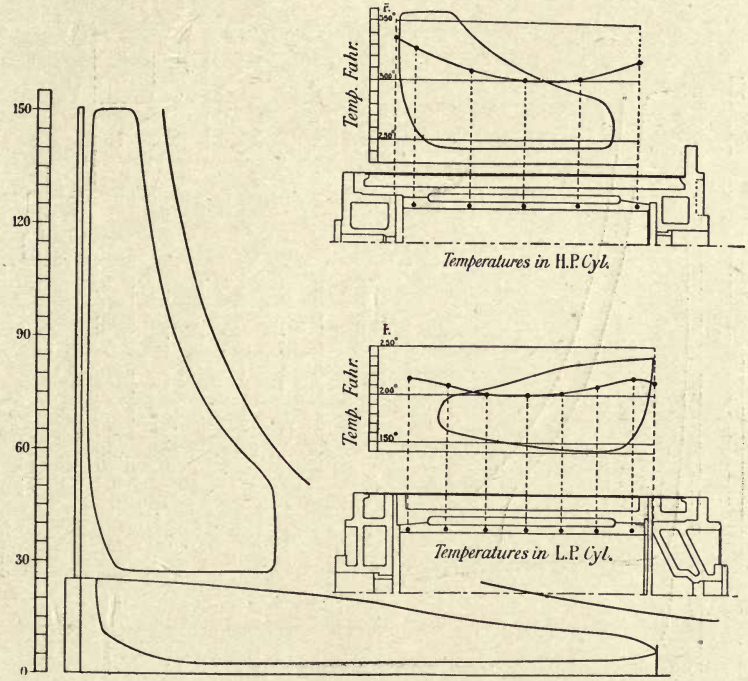


FIG. 51.—Pressures and temperatures in steam engine cylinders. (No steam in jackets.)

various materials having water flowing through the central hole and steam outside the cylinder. Many interesting results were obtained which are too extensive to enumerate here, and the reader should refer to the original papers for further particulars, though in view of the newer experiments made since his time some of the results are now relatively of less importance.

* *Proc. Inst. Civil Eng.*, Vol. C, 1889–90, Part II; *ibid.*, Vol. CVI, 1890–91, Part IV; *ibid.*, Vol. CXV, 1893–94, Part I; *Proc. Inst. Mech. Eng.*, 1893, p. 480; *ibid.*, 1895, p. 90; *ibid.*, 1896; *ibid.*, 1900, p. 509.

Messrs. Callendar and Nicolson have made experiments on the rate of condensation of steam at the temperatures obtaining in steam engine cylinders, using a thick-walled condenser about 24 in. long with mercury thermometers inserted in holes bored in the metal. They found that the rate of condensation was not appreciably altered by using revolving brushes to

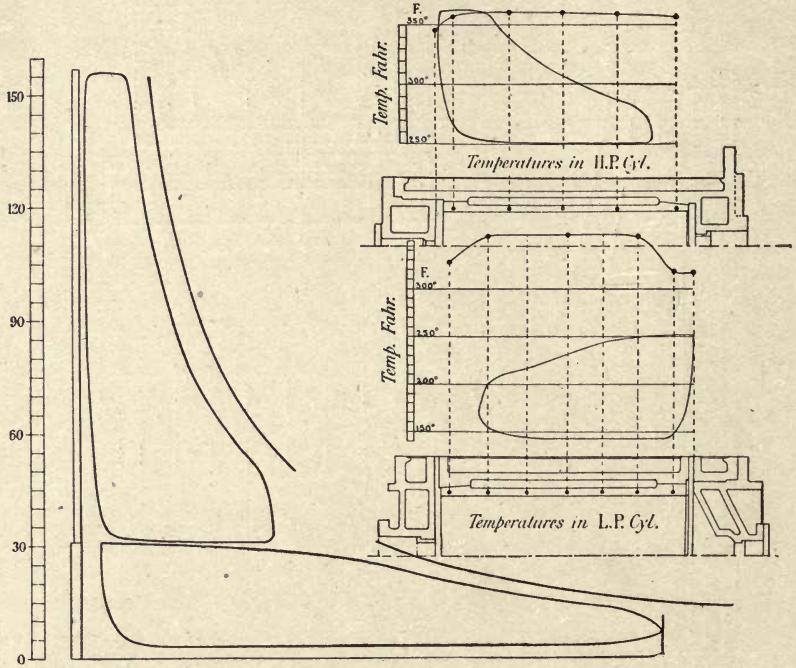


FIG. 52.—Pressures and temperatures in steam engine cylinders. (Steam in all jackets.)

sweep over the condensing surface five or six times per second, and they concluded that the maximum rate of condensation was about 0·74 B.Th.U. per square foot per second per degree Fahr. difference of temperature between the steam and the wall.

In some experiments made by Professor A. L. Mellanby*

* "An Investigation to Determine the Effects of Steam-Jacketing upon the Efficiency of a Horizontal Compound Steam-Engine," *Proc. Inst. Mech. Engs.*, June, 1905.

on a horizontal compound side-by-side steam engine, with high pressure cylinder 11½ in. diameter, low pressure cylinder 20 in. diameter and stroke 36 in., mercury thermometers were inserted at various points along the length of the cylinder liners as represented in Figs. 51 and 52. Here also is shown the mean temperatures in the metal compared with the saturation temperatures of the steam in the cylinder as determined

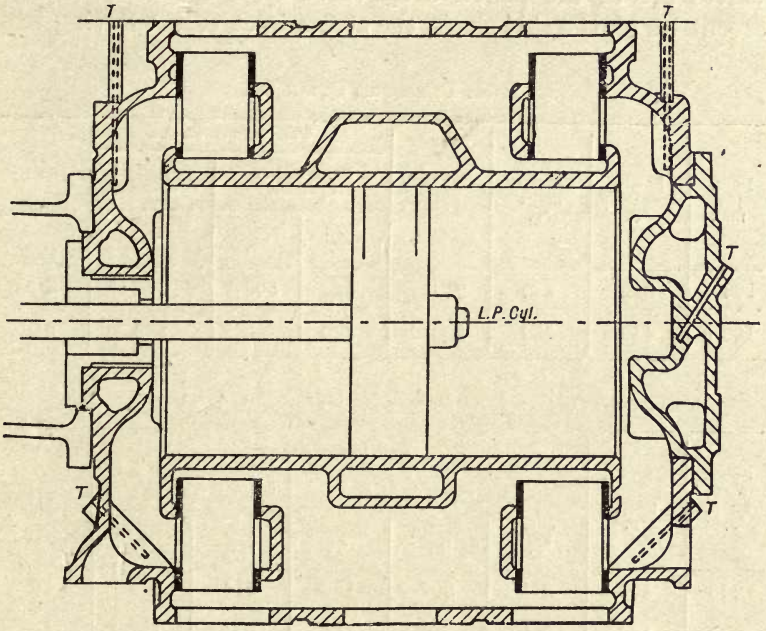


FIG. 53.—Section through L.P. steam engine cylinder having drop piston valves. Thermometers in drilled holes T.

from the pressures on the indicator diagrams. Fig. 51 illustrates the conditions without steam in the jackets, while Fig. 52 shows the effect of steam in all the jackets. In both cases the engine was running at about 60 revolutions per minute with the nominal total number of expansions 12·3.

The representative data given in the following table were obtained from a horizontal compound side-by-side steam engine installed in the mechanical engineering laboratory at The Royal Technical College, Glasgow. The low pressure

cylinder, 21 in. diameter, with stroke 30 in., is shown in section in Fig. 53. The high pressure cylinder, 12 in. diameter with stroke 30 in., is similar in construction. Mercury thermometers can be inserted in drilled holes at the positions marked T in Fig. 53 in the low pressure cylinder, and also in similar holes in the high pressure cylinder, though only at the top of both ends and in the middle of the cover of the h.p. cylinder. The valves are of the piston drop valve type operated through eccentrics on the side shaft, the steam inlet valves having trip gear.

HIGH PRESSURE CYLINDER

Revs. per min.	Steam chest temp. °F.	Saturation temp. °F.	Exhaust temp. °F.	Wall temperatures.			Cut-off per cent of stroke.
				Cover end of cylinder.		Crank end of cylinder.	
				Top. °F.	Middle. °F.	Top. °F.	
102	352	352	229	327	309	305	22·5
100·8	433	352	223·5	* over 340	—	322	21

LOW PRESSURE CYLINDER

Steam chest temp. °F.	Exhaust temp. °F.	Wall temperatures.					Cut-off per cent of stroke.
		Cover end of cylinder.			Crank end of cylinder.		
		Top. °F.	Middle. °F.	Bottom. °F.	Top. °F.	Bottom. °F.	
229	136	211	207	195	214	200	50
223	130	200	—	181	204	186·5	40

The illustration Fig. 54 relates to a single cylinder central exhaust engine installed in the mechanical engineering laboratory at The Royal Technical College, Glasgow. The steam inlet valves are of the piston drop valve type with trip gear; the cylinder diameter is 11 in. and the stroke 30 in. The length of the engine piston is such as to allow both ends to overrun the central ports and through these ports the steam exhausts from the two ends alternately. Therefore the steam shut in the cylinder when the ports are covered on the return of the

* Beyond the range of the 340° F. thermometer.

piston is compressed into the clearance space as is shown by the indicator diagrams. The positions of the thermometer holes, T, drilled in the cylinder wall are shown in the plan sectional view of the cylinder in Fig. 54. Typical indicator

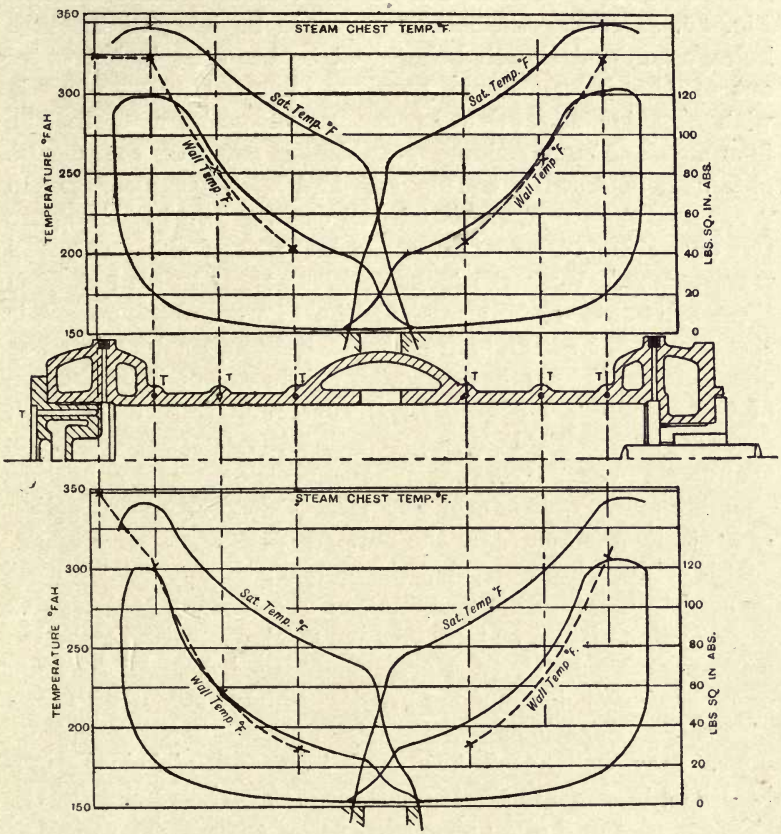


FIG. 54.—Pressures and temperatures in a steam engine cylinder with central exhaust. Thermometers T in drilled holes.

diagrams are reproduced for two tests at different cut-offs when using saturated steam, and saturation temperature curves, obtained by the use of steam tables from the indicator diagrams, are also shown for the admission, expansion, and exhaust portions of the cycle. There is also shown plotted

the actual mean wall temperatures as measured by mercury thermometers at the points indicated.

In a small gas engine experimented with by Messrs. Coker and Scoble, *Proc. Inst. Civil Engs.*, Vol. CXCVI, thermometer holes were bored into the liner at the various points shown in Fig. 55. Mercury thermometers could be inserted in these holes, a screwed sheath being used to keep the jacket water out of the holes. Some previous experiments were made with the jacket outlet in the usual position O in the figure, and Fig. 56 shows graphically some of the results obtained both with town's gas and with producer gas in use. It will be noticed that in all cases shown in this figure the outlet jacket temperature is lower than the mean wall temperature. With the jacket outlet at AO instead of at O the results shown graphically in Fig. 57 were obtained. It is there seen that with a high outlet jacket temperature this was above the wall temperature at all points except in the region of the combustion chamber. These graphs also show that, speaking generally, in any given test the temperature along the barrel was nearly constant except at the combustion chamber end. This is probably largely due to the convection of heat along the liner by the moving piston.

It is evident, however, that the mercury thermometer cannot be used to measure the temperature of a moving part such as a gas engine piston, or to determine the temperature of a thin wall such as a boiler tube or a condenser tube. Under such circumstances it is the usual practice to have recourse to suitable thermo-junctions.

Professor Callendar* has used iron and nickel thermo-junctions to measure the temperatures at various points of the thin cylinder wall of an air-cooled petrol engine. The wires of iron and nickel were about one millimeter in diameter and each pair forming a couple were firmly screwed, side by side, into small holes in the cylinder (cast iron) so as to get good electrical and thermal contact.† Eight couples were employed

* "Some Experiments on an Air-Cooled Petrol Motor," *Technics*, April, 1904.

† This is equivalent to connecting the nickel and iron wires together to form the couple, provided the connecting material, in this case cast-iron, is homogeneous and at the same temperature as the connected ends of the wires.

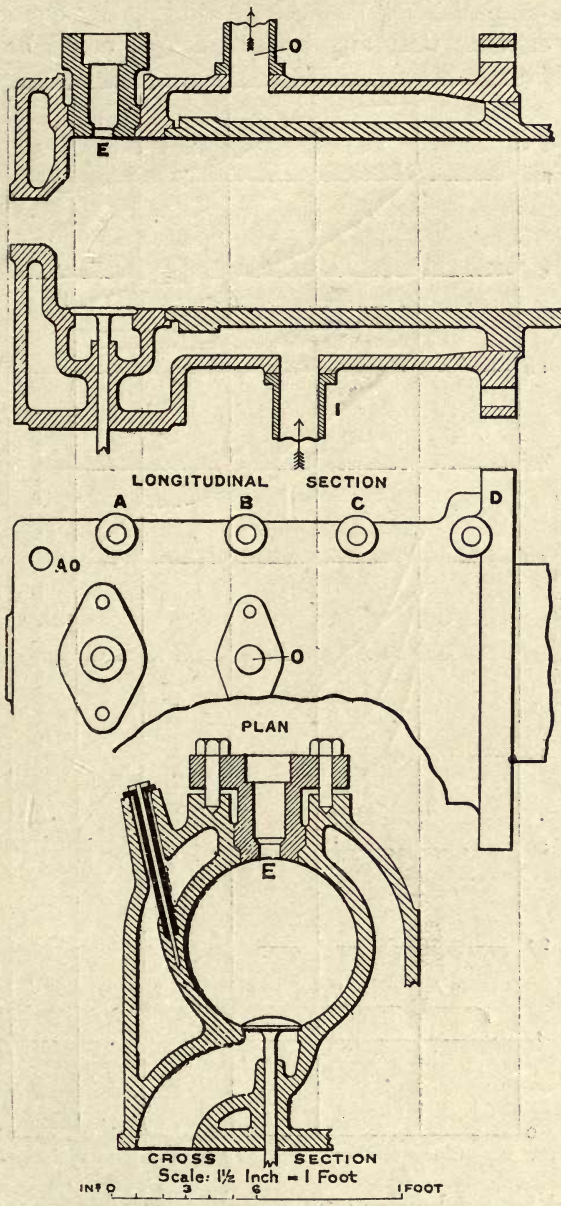


FIG. 55.—Gas engine cylinder with drilled thermometer holes in liner at A, B, C, D.

in different positions, the other ends being connected to mercury cups so that any desired couple could be quickly

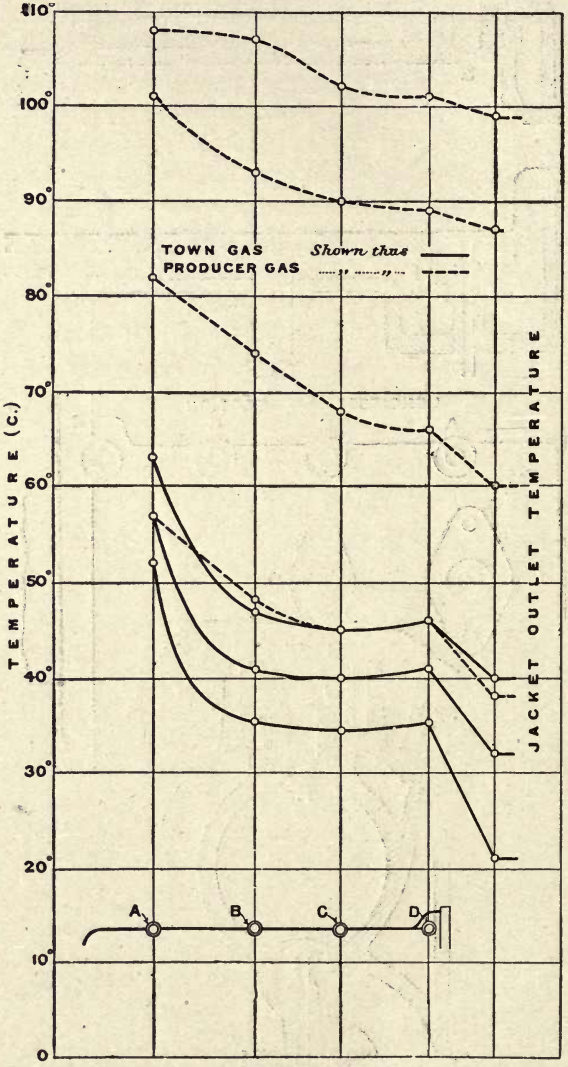


FIG. 56.—Liner temperatures in a gas engine cylinder.

connected to a galvanometer or millivoltmeter for measuring the electromotive force. One of the couples was calibrated

against a standard platinum-resistance thermometer ; it was found that the thermoelectric power* of the couple fell to less

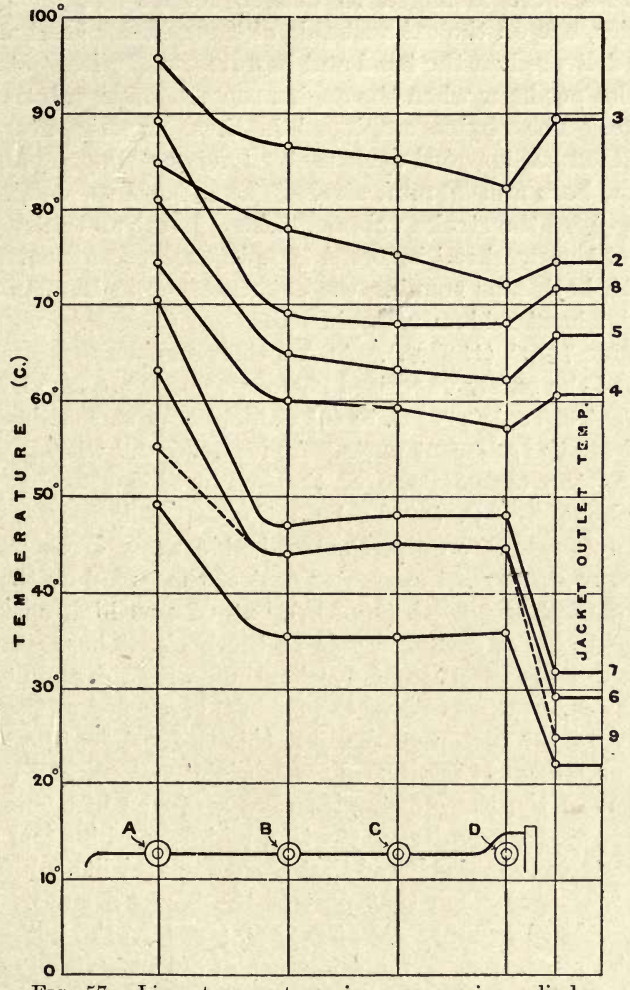


FIG. 57.—Liner temperatures in a gas engine cylinder.

than half its initial value between 300° C. and 400° C., but increased again at higher temperatures.

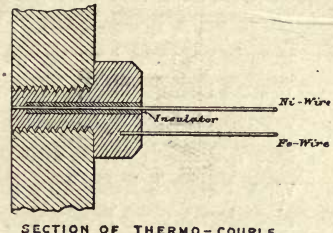
* The term "thermoelectric power" is usually taken to refer to the rate at which the e.m.f. (E) changes with the temperature (T), that is $\frac{dE}{dT}$.

To enable the engine to be run on the stand without overheating, and to imitate somewhat the conditions on the road, two fans were arranged to deliver currents of air on the cylinder, one on the exhaust side of the cylinder head and the other delivered on the head and barrel from the front at about 25 miles per hour when the engine ran at 2000 revolutions per minute. The engine employed in these experiments was a small Clement-Garrard cycle motor having a single cylinder of 60 mm. bore and 70 mm. stroke. The clearance volume was about $\frac{3}{10}$ of the stroke volume. The exhaust and inlet valves were of the overhead inverted type in the cylinder cover.

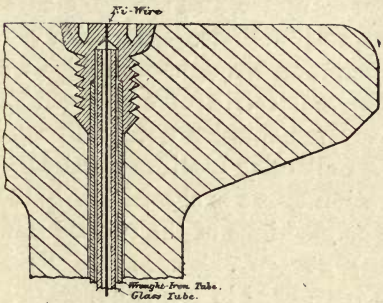
With both fans running the exhaust side on the top of the cylinder head seldom rose above 300° C. (572° F.) and at the inlet side 70° C. (158° F.). At full throttle opening the cooling effect of the partly vaporised petrol was so great that the inlet was kept as cool as 30° C. to 40° C. in spite of the conduction of heat from the adjacent parts. At full load and with both fans running the temperature of the combustion chamber never rose above 200° C. (392° F.) on the exposed side, or above 260° C. (500° F.) on the sheltered side away from the fan. The temperature of the greater part of the barrel on the front side was below 150° C. (302° F.), but rose as high as 200° C. (392° F.) on the sheltered side at the back. These were well below the temperature of overheating, which does not begin until a temperature of 300° C. (572° F.) is reached at the upper portion of the piston stroke, but this is dependent somewhat on the quality of the oil used for lubrication.

Three of the thermo-couples were arranged in a line down the side of the cylinder, at the top, middle, and bottom of the piston stroke. It was found that there was very little difference of temperature along that part of the barrel surface. When the top thermo-couple was at 200° C. (392° F.) the bottom one was at 180° C. (356° F.), a difference of only 20° C. in 70 millimeters. The reason for this is that, in a high-speed engine particularly, convection of heat by the piston plays a much more important part than conduction in the longitudinal distribution of temperature. The same phenomenon was noted in connection with the water-cooled gas engine on p. 110.

The late Professor Hopkinson* also used the wrought-iron, nickel thermo-couple to measure the mean temperatures at particular points of the uncooled piston, exhaust valve, and inlet valve of a Crossley gas engine working on the Otto cycle. The cylinder diameter was $11\frac{1}{2}$ in. and the stroke 21 in., and the engine was designed to give a maximum of 40 B.H.P. at 180 revolutions per minute. The compression pressure was higher than usual, being about 160 lbs. per sq. in. above atmospheric pressure. The ignition was by magneto and the governing by hit and miss. Cambridge coal gas was used as the fuel throughout these experiments.

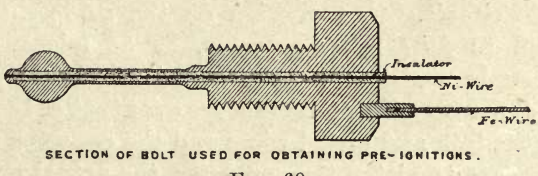


SECTION OF THERMO-COUPLE USED IN PISTON.
FIG. 58.



SECTION OF THERMO-COUPLE USED IN EXHAUST-VALVE.
FIG. 59.

The arrangement of the thermo-couples is shown in Figs. 58, 59 and 60. Fig. 58 shows the construction of one of the piston thermo-couples, of which three were used, one at the centre and the other two at different radii from the centre. The one used in the exhaust valve is illustrated to full size in Fig 59, and a similar thermo-couple was used in the inlet valve. The



SECTION OF BOLT USED FOR OBTAINING PRE-IGNITIONS.
FIG. 60.

thermo-couple shown in Fig. 60 was arranged to project into the centre of the combustion chamber in order to study the

* "Heat Flow and Temperature Distribution in the Gas Engine," *Proc. Inst. Civil Engs.*, Vol. CLXXVI.

temperatures at which such a projection would cause pre-ignitions. Each thermo-couple consisted of a nickel wire brazed into the wrought-iron bolt. The nickel wire was passed through a hole drilled along the axis of the bolt from which it was insulated by means of a glass tube set in plaster of Paris ; it was then brought through a small hole at the end of the bolt, where it was brazed to the iron, and the end of the wire was cut off flush with the end of the bolt. A wrought-iron wire was brazed into the head of the bolt, and to complete the circuit copper leads were sweated to the nickel and iron wires respectively at a distance of 3 feet or so from the bolt, connecting the thermo-couple through an adjustable resistance to a reflecting galvanometer.

The nickel wire was obtained from Messrs. Johnson, Matthey and Co. ; it was ·015 in. diameter, and the same batch of wire was used for all the thermo-junctions. The bolts were of ordinary wrought-iron, and common wrought-iron wire was used. There was no material thermoelectric force between the iron wire and the bolt. The thermo-couples were calibrated in an electric furnace against a Callendar platinum resistance pyrometer and one such calibration curve is shown in Fig. 61, with the cold junction (i.e. the connections of the copper leads to the iron and nickel wires) at 0° C. The same leads, resistances, and galvanometers were used in the calibration as in the engine, the bolt containing the couple being simply transferred from its place in the engine to the furnace. It was thus possible to use a low resistance galvanometer ; about 5·8 ohms for galvanometer and leads, making 21·8 ohms for the whole circuit. One division on the galvanometer scale was equal to 2·57 micro-amperes, or 56 microvolts. The thermo-couple registered, with sufficient accuracy for the purpose, the excess of its temperature over that of the junctions between the iron and nickel wires and the copper leads.

With regard to piston temperatures, the actual temperature at the centre of the piston, with the jacket outlet temperature of 70° C. (158° F.), was about 370° C. (698° F.) when the total heat loss to the jacket water was about 1600 B.Th.U. per minute, and it was estimated that under these conditions the temperature at the edge was about 182° C. below that at the

centre. The highest recorded temperature at the centre of the piston was 480° C. (896° F.).

Under ordinary running conditions with a medium gas-charge and with a loss of about 1600 B.Th.U. per minute to the jacket, the temperature at the centre of the exhaust valve

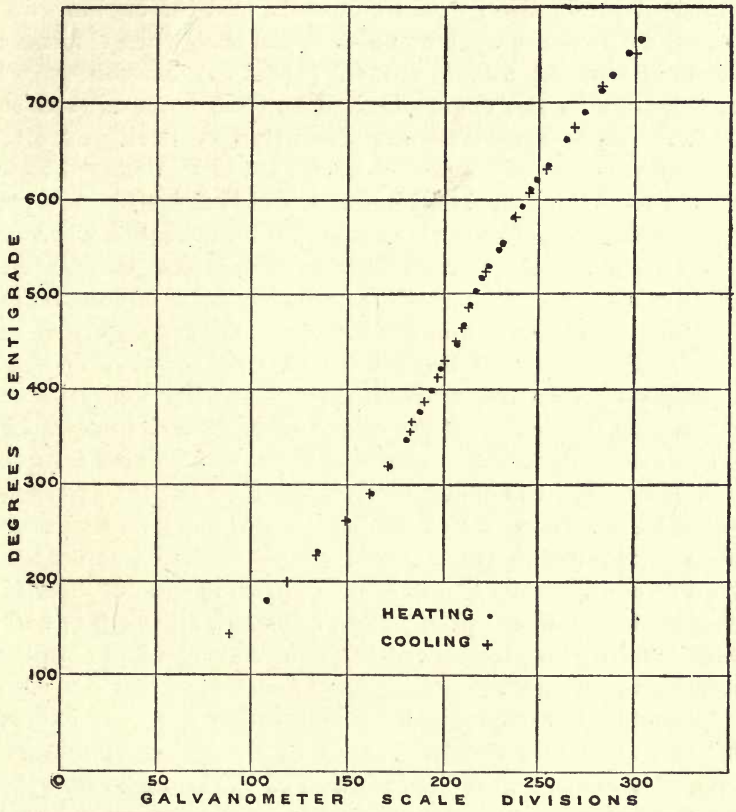


FIG. 61.—Calibration curve for wrought-iron, nickel thermo-couple.

was about 400° C. (752° F.), and at the centre of the inlet valve about 250° C. (482° F.). With heavy charges the exhaust valve may reach 500° C. (932° F.). All these results compare fairly well with those obtained by Messrs. Coker and Scoble summarised on p. 139. Although the thermo-couples showed small cyclical fluctuations of temperature it was not possible

to calculate the fluctuation of the surface temperature because the recorded fluctuations only represented a kind of average result over a thickness of about $\frac{3}{16}$ of an inch.

When the thermo-couple shown in Fig. 60 was inserted it was found that if the gas mixture was rich enough to raise the temperature of the end to a little above 700° C. (1292° F.) persistent pre-ignition would be caused and the engine would be rapidly pulled up. It was also found that when the end of the bolt reached about 800° C. (1472° F.) back-firing was caused, that is, the charge ignited as soon as it entered the engine. An arrangement was also fitted vertically over the exhaust valve by means of which oil could be dropped on to the centre of the valve, and it was found that in this way pre-ignitions of considerable violence could be produced when the exhaust valve had a temperature as low as 450° C. (842° F.), but of course, these pre-ignitions only persisted so long as the oil was allowed to drop on the hot surface.

A large number of tests were also made with different strengths of mixture, and within fairly wide limits it was found that the temperature of pre-ignition was independent of the strength of the mixture. Injection of water into the engine, through the suction-valve provided for that purpose, reduced the rate of rise of temperature of the bolt and sometimes prevented it from reaching the critical temperature. Even in considerable quantities, however, it did not alter the temperature at which pre-ignition occurred, although it had a tendency to prevent the critical temperature of pre-ignition from being attained.

Although it is convenient for calibration purposes to have the thermo-couple constructed as in Professor Hopkinson's tests, it is evident that the insertion of the wrought-iron plug in the cast iron involves a screwed joint which may not be in the same condition as the normal body of the cast iron, and the plug may attain a temperature several degrees higher than the cast iron. There is also the possibility of parasitic or localised currents being set up by the contact of the wrought-iron plug and the cast iron, though it must be said that it is hardly likely such would affect the thermo-couple at the centre of the plug.

In the arrangement of the iron-nickel thermo-couple as

used by Professor Callendar, and described on p. 110, the iron and nickel wires were screwed side by side into the cast iron of the cylinder. Provided that the cast iron in the neighbourhood of the junction is quite homogeneous its presence should make no difference to the electromotive force at a given temperature ; but cast iron is very liable to non-homogeneity, either in structure or in the internal stresses, and thus there is some liability of small parasitic or local thermoelectric currents affecting the recorded electromotive force of the junction.

As mentioned on p. 40, base metal thermo-couples are very liable to alterations of thermoelectric force in course of time with prolonged usage. For experiments of comparatively short duration there is probably not much difficulty—in fact, Professor Hopkinson said that he had no difficulties with his thermo-couples due to prolonged exposure—but Colonel Crompton, in discussing Professor Hopkinson's paper,* reported that he himself had not succeeded in getting satisfactory results with iron-nickel thermo-couples, instancing a case where such a couple underwent a decrease of 10% to 15% in thermoelectric force in the course of six months after the couple was first put together, with exposure to temperatures of about 700° C. (1292° F.).

In the experiments made by Dr. T. E. Stanton† on the transmission of heat between water and a copper tube the mean temperature of the tube during each experiment was obtained by measuring its increase of length. The arrangement consisted of a wrought-iron tube fixed parallel to the copper tube at a distance of $3\frac{1}{2}$ in. This W.I. tube was surrounded by a water-jacket so as to keep it at a uniform temperature. A long light lever, hinged on the top of the copper tube, had a knife edge bearing on the top of the W.I. tube, and the lever was extended to move over a scale so that 1 mm. movement of the pointer represented 0·5° C. change of temperature of the copper tube. Before and after any experiment the temperature corresponding to the scale reading was determined by trial since the mean tube temperature was given by the mean temperature of the water flowing through the apparatus.

* *Proc. Inst. Civil Engs.*, Vol. CLXXVI, 1908–09, Part II, p. 46.
† *Trans. Royal Soc.*, 1897, Section A.

Although the method adopted to measure the mean tube temperature suited the particular conditions of the experiments, it cannot be recommended as of general application because of the uncertainty as to the permanence of the relative coefficient of expansion, and also the end effects on the tube are somewhat uncertain.

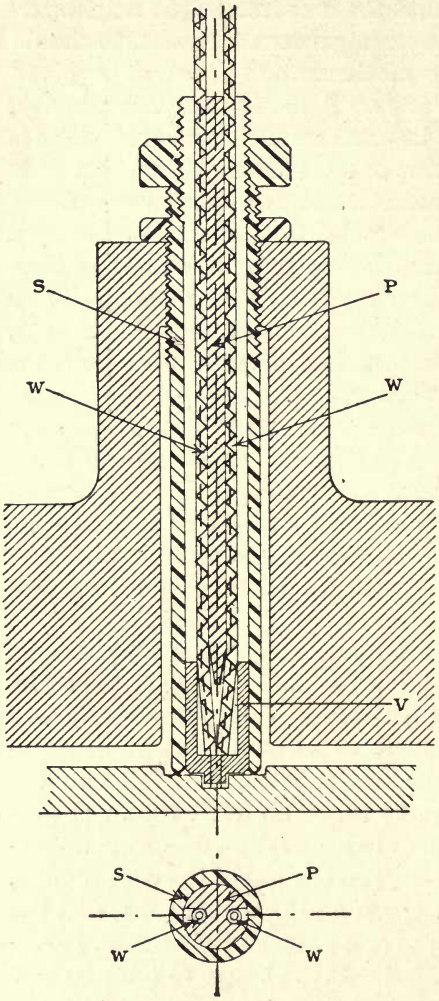


FIG. 62.—Jordan's arrangement of thermo-junction for temperature of copper tube.

A copper-constantan thermo-couple was used by H. P. Jordan,* working under the late Professor J. T. Nicolson, to determine the temperature of a copper tube through which heated air was flowing, the tube being cooled by water circulated on the outside of the tube. The particular arrangement of the thermo-couple is shown in Fig. 62. First, a steel, or in some experiments a gun-metal, sheathing, S, was screwed up tight, till its knife-edge end had made a water-tight joint with the internal copper air-pipe, and thus excluded the water from this portion of the pipe. Into this sheathing was screwed a long copper plug, P, with two longitudinal slots in which were laid the insulated copper and constantan wires W. To the copper plug was keyed a

* *Inst. Mech. Engs.*, 1909, p. 1317.

hollow vulcanite end, V, so that copper and vulcanite turned together. The end of the vulcanite was solid and turned down to fit into a small recess of $\frac{1}{8}$ in. diameter drilled to a depth in the metal of the copper pipe equal to half its thickness. Two small pinholes were drilled through the small end of the vulcanite. The insulated copper and constantan wires were laid in the slots in the copper plug, and then brought inside the vulcanite end. For a short distance (about $\frac{1}{4}$ in.) at their ends the wires were stripped of their insulation, and this length was pushed through the pinholes in the small end of the vulcanite, thus leaving the two ends standing out from about $\frac{1}{64}$ to $\frac{1}{32}$ in. and about $\frac{1}{20}$ in. apart. The wires were then fixed in the slots by shellac. To make the junction, the copper plug was carefully screwed up until it was felt that the end was fitted well up against the internal pipe. Great care was taken that the small vulcanite end should fit into the recess in the metal of the pipe ; this was done by testing, with a gauge and cutter, the exact size of the vulcanite end before fitting in the junctions. The cold junction was kept at a constant known temperature by means of an oil-bath.

The direct deflection method was used to measure the electromotive force produced by the difference of temperatures of the hot and cold junctions, the galvanometer being of the D'Arsonval mirror type. The deflections on the galvanometer scale were carefully calibrated by keeping one junction in a cold oil-bath of constant temperature and heating the other junction in a second oil-bath by means of a Bunsen burner, the temperatures of both oil-baths being taken by standard mercury thermometers. From these results a curve was drawn connecting temperature differences of the junctions with the galvanometer deflections. By the aid of these curves the metal temperatures were inferred from the galvanometer deflections observed during the course of the experiments. An objection to this particular arrangement of the thermo-junctions might be urged on account of the appreciable surface of the tube which is excluded from contact with the water by the sheath S, and which might thus slightly affect the temperature at this point. There does not appear to be any reason

why the sheath should not be reduced in diameter in the neighbourhood of the junction and the vulcanite end V made to suit.

Although this arrangement is suitable where the temperature of the tube is comparatively low there is likely to be some difficulty in keeping the joint between the tube and the end of the sheath tight against leakage when the tube has a relatively high temperature, because of the larger relative expansion between the copper tube and the cast-iron body of the apparatus.

Messrs. Clement and Garland* have used copper-constantan thermo-couples to measure the temperature of a cold-drawn steel tube of ·985 in. bore, and outside diameter 1·253 in., through which water was allowed to flow, the outer surface being in contact with steam. The temperature of the tube was obtained at two points near the two ends of the tube. The ends of the couples were soldered into small holes about $\frac{1}{32}$ in. diameter and about $\frac{1}{64}$ in. deep which were drilled in the tube. The leads were conducted through small glass tubing to special flanges on the external cast-iron cylinder and then between two rubber gaskets placed between the flanges. The thermo-couples were connected up to a Siemens and Halske millivoltmeter.

Whilst such an arrangement causes little or no disturbance of the thermal conditions at the point of connection to the steel tube it involves the carrying of the wires through the condensing steam and is therefore not a desirable arrangement under such conditions.

The arrangement shown in Fig. 63 was devised by Professor A. L. Mellanby and was used by G. C. Webster† in his research at The Royal Technical College, Glasgow, on the "Condensation of Steam," referred to fully in *Heat Transmission in Boilers, Condensers, and Evaporators.* The copper and constantan wires forming the thermo-couple are not shown in the illustration, but they passed down the centre of the steel sheath to make contact with the copper tube. These wires were caulked into holes in the tube about $\frac{1}{16}$ of an inch

* *Bulletin* 4, 1909, Univ. of Illinois Engineering Experiment Station.
† *Trans. Inst. Engs. and Shipbds. in Scotland,* Vol. LVII, 1913–14.

deep, the ends of the wires being swelled slightly to get a good contact in the holes. To enable this to be done easily the steel sheath shown in Fig. 63 was made in two parts, the bottom part brazed on to the copper tube and the upper part screwed into this bottom part. A nut at the top formed a steam joint flexible enough to allow for the relative expansion of the tube, and at the same time kept all parts of the sheath pressed downwards to minimise the danger of leakage into the centre of the sheath. It would be noticed that this arrangement excludes a certain small portion of the tube from contact with the steam, but the method of calibrating the thermo-couples, suggested by the writer, minimised the possibility of errors from this cause. In the actual apparatus a connection with a shut-off cock between the steam and water inlets was provided. The water outlet could also be connected to another condenser so that steam or hot water could be passed through on both sides of the tube when required for calibration purposes. By this means both sides of the copper tube could be flooded with steam or hot water, arranged to flow through at a sufficient rate so as to keep very nearly a constant temperature at all parts of the tube. This temperature was observed by calibrated mercury thermometers placed in pockets at the inlet and outlet, and thus the tube temperature was known fairly accurately during the calibration.

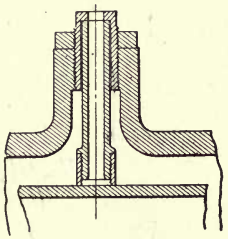


FIG. 63.—Arrangement for shielding thermo-junction in copper tube.

The potentiometer method of measuring the electromotive force was adopted. Referring to Fig. 64.

A is the wire of the potentiometer.

B a storage cell which maintains a potential difference between the ends of the wire A.

HJ and CJ are the hot and cold junctions respectively.

Rh. is an adjustable rheostat.

R a constant resistance.

C a standard cell.

SS two-way switches.

G_1G_2 sensitive galvanometers.

The wire marked E was made of constantan, but all the other wires were of copper.

This arrangement is much the same as that described in connection with Fig. 26, p. 51, and Fig. 76, p. 137, and, briefly stated, was operated as follows :—

When the standard cell C was connected up as shown and the resistances readjusted till the galvanometer G_1 showed no deflection, the potential drop across R and A was equal to the constant electromotive force of the standard cell C. For any temperature difference of the hot and cold junctions there was a corresponding electromotive force in the thermo-couple circuit which could be balanced by a part of A, balance being indicated when the galvanometer G showed no deflection.

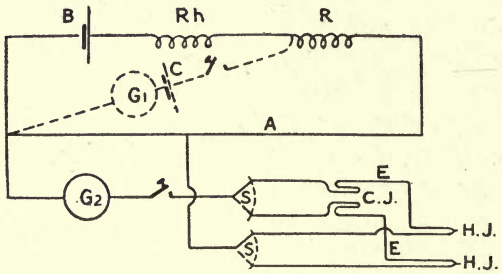


FIG. 64.—Diagrammatic arrangement of potentiometer used in Webster's experiments.

The cold junction for these experiments was kept in melting ice, and, as already explained, for calibration purposes the tube could be arranged to have any desired temperature, so that curves were easily obtained connecting the tube temperatures and the length read on A. These curves were then used in the experiments for translating potentiometer readings to tube temperatures. It was found that about 1 cm. length of the wire was equivalent to 1° F., and therefore $\frac{1}{10}$° F. could easily be read. These calibration curves were tested at intervals throughout the experiments but never varied appreciably.

Before the arrangement for the thermo-junctions shown in Fig. 63 was adopted one was tried of the type used by Mr. Jordan, Fig. 62, p. 120. With the comparatively high tube

temperatures obtained, however, there was so much trouble with the leakage of steam under pressure, probably due to relative expansion of the condenser tube, that the arrangement had to be discarded in favour of that shown in Fig. 63.

From the observed temperatures at two points along a tube it is possible to calculate the temperature at any similar point along the length of the tube, and also to calculate the temperature at any distance from the surface when the conductivity of the metal is known.

E. M. Bryant* has used thermo-junctions to measure the temperature of metal plates forming the bottom of a small boiler evaporating water at atmospheric pressure. After trying various arrangements that shown in Fig. 65 was finally adopted as causing the least disturbance to the flow of heat through the metal. A small plug of circular section, of the same metal as the plate, was made to fit into a slightly tapered hole so that its ends were level with the surfaces of the plate. Two holes, $\frac{1}{16}$ in. in diameter, were drilled lengthwise on opposite sides of the plug to the desired depth, and they were connected by a horizontal hole of the same diameter. There were six such plugs arranged in a circle of $1\frac{1}{4}$ in. radius round the centre of the plate and at various depths in the metal. The junction formed a bead fitting loosely into the horizontal hole in the plug, and was fixed in position by solder. The remaining space in the holes was filled up with very fine Portland cement. A little rubber solution was used between the plug and the plate to ensure its being watertight. The connecting wires from the junction were covered by asbestos within the holes, and enclosed within rubber tubes, passed directly through the water.

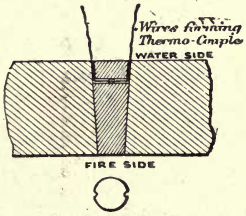


FIG. 65.—Plug in plate containing thermo junction.

The e.m.f.'s of the thermo-junctions were measured by means of a Déprez-D'Arsonval galvanometer which could be read to 0·2° C. A calibration curve was drawn for each junction, using the known boiling points of steam (212° F.), aniline (363° F.), and naphthalene (424·5° F.).

* *Proc. Inst. Civil Engs.*, Vol. CXXXII, 1897-98.

In the Technical Paper No. 114, issued by the Department of the Interior, Bureau of Mines, Washington, U.S.A., experiments are described in connection with the measurement of the temperature of boiler tubes and the transmission of heat. Copper-constantan thermo-couples were used embedded in the metal of a tube in the bottom row of tubes in a water-tube boiler where the hot gases entered among the tubes. A couple was also placed in a tube in the highest row where the gases left the boiler. The arrangement of the thermo-junctions is

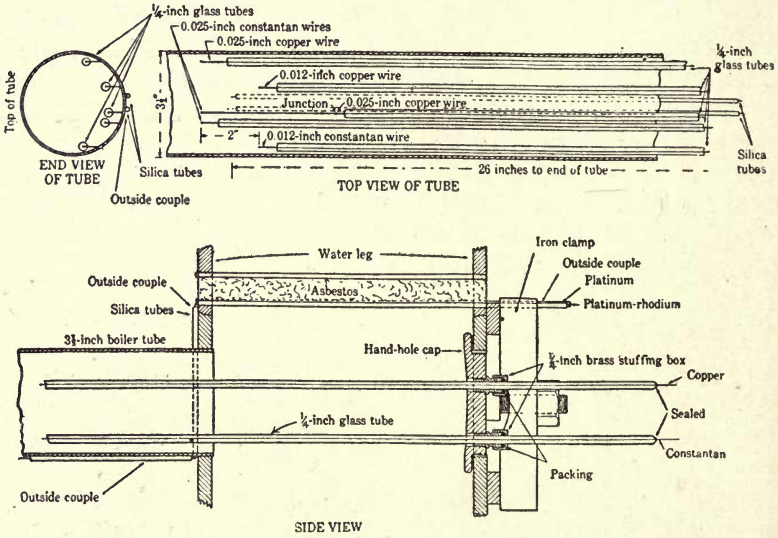


FIG. 66.—Arrangement of thermo-junctions to measure the temperature of a boiler tube.

shown in Figs. 66 and 67. The hot junctions were formed by embedding the constantan and copper wires separately in the metal of the tube, and the method adopted for fixing these wires in the metal is shown in Fig. 68. A hole was drilled in the tube to a depth of about one-sixteenth of an inch and about ·001 in. larger in diameter than the wire, and the end of the wire was then pinned in with the special hollow tool having a cup-shaped end as shown in Fig. 68. Two or three light taps with an 8-oz. hammer were sufficient to pin the wires in the tubes so tightly that the wire would break rather than pull out of

the hole. The thermo-couple wires on the inside of the tube were at first insulated by being passed through thick-walled $\frac{1}{4}$-in. glass tubes, which passed through brass stuffing boxes fitted in the hand-hole cover opposite the boiler tube. The hole in the glass tubing was so small that leakage of steam and water was insignificant. It was found, however, that the glass tubing was attacked by the boiler water and gradually it became soft and opaque, and disintegrated after about five days' usage. In later experiments small porcelain tubes were used and it was found that these were not appreciably affected by the boiler water and steam. The couples on the outside of the boiler tube were of platinum, platinum-rhodium wires insulated by silica tubes.

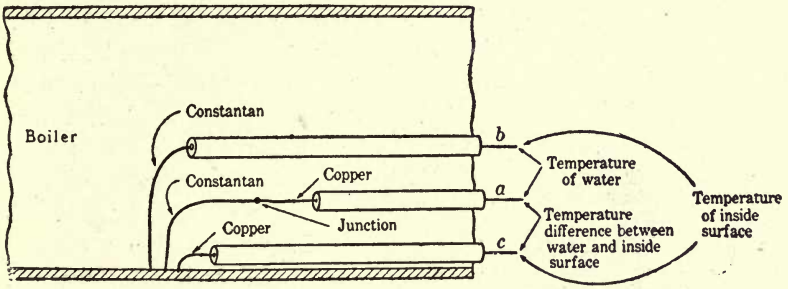


FIG. 67.—Diagrammatic arrangement of thermo-junctions.

The method of measuring the difference of temperature between the inside surface of the boiler tube and the water is illustrated diagrammatically in Fig. 67. By using the wires (*b*) and (*c*) the temperature of the metal was obtained. Using (*a*) and (*b*) gave the temperature of the boiler water, the two constantan wires in the metal then being neutral. In both these cases the cold junction was at any convenient place and temperature outside the boiler. Using (*a*) and (*c*) gave the difference between the temperature of the metal (hot junction) and the boiler water (cold junction). In all cases the e.m.f. was obtained by the potentiometer method. The temperature of the boiler water was also observed independently by a couple formed of a closed $\frac{1}{4}$-in. copper tube having a constantan wire fused in the closed end. The results obtained with this

couple compared very closely with those obtained with the wires (*a*) (*b*) in Fig. 67.

To ascertain the effect of electrical leakage and galvanic action of the boiler water where the leads are passed through the boiler water as in Fig. 66, special experiments were made by fixing two copper and two constantan wires into an iron strip in the manner described on p. 126, thus forming two thermo-couples. The leads of one thermo-couple were taken through a 3-in. pipe and brought out through the cap in a manner similar to that used for the boiler thermo-couples, the length of this pipe being arranged so that the leads were surrounded by water for about the same length as in the boiler tube. The leads of the other thermo-couple were in air. Before any water was run into the pipe a calibration was made, showing that the two couples read exactly alike. Hot water from the boiler was then circulated through the test pipe so that the same water and pressure were used as in the boiler tube. It was found that the readings of the thermo-couple with the leads immersed in the pipe were ·12 to ·15 millivolt too high when the true potential generated by the couple was about 7 millivolts, and this was equivalent to a temperature reading too high by about 3° C. Hence 3° C. was subtracted from the temperatures indicated by the thermo-couples in the boiler tube to give the true temperatures.

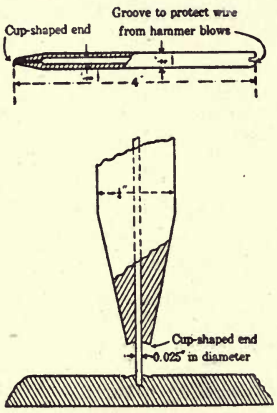


FIG. 68.—Method of fixing wires of junction into tube.

The results obtained are discussed in *Heat Transmission by Radiation, Conduction, and Convection*, the most important feature shown by these results being that the temperature of the tube was within 10° F. to 20° F. of that of the boiler water.

The fusion points of metal alloys have also been used to estimate the temperature of heating surfaces, as, for instance, that of the heating surface of boilers. In this method the alloys of various melting temperatures are inserted a good fit

in holes sunk in the boiler plate or tube and the temperature of the plate is taken to lie between the melting point of the last one to fuse and the next higher in fusing temperature which remains solid. Sir A. J. Durston, for instance, used this method to estimate the temperature of the heating surfaces at various points of a model boiler.* The method, however, is now considered to be somewhat crude and much inferior to thermo-junctions under skilful manipulation.

* *Trans. Inst. Naval Arch.*, 1893.

CHAPTER VIII

THE MEASUREMENT OF RAPIDLY FLUCTUATING TEMPERATURES

It is well known that the inner surface of the cylinder of a steam engine or a gas engine fluctuates in temperature in response to the varying temperatures of the fluid in contact with the surface. This fluctuation of the surface temperature, however, is comparatively small, and does not penetrate far into the metal, as is demonstrated fully in *Heat Transmission by Radiation, Conduction, and Convection.* Mr. Bryan Donkin* attempted to measure the range of fluctuation of temperature in a steam engine cylinder by using very delicate mercury thermometers of small diameter inserted in holes at various distances from the inner surface. Although he observed a fluctuation of temperature near the surface, this method was not successful on account of the appreciable lag of the thermometers.

Thermo-junction methods were tried by Professor E. Hall of Harvard College,† but with only limited success. Professors Callendar and Nicolson‡ seem to have been the first experimenters to use thermo-junctions successfully for the measurement of the fluctuation of temperature in the cover of a steam engine cylinder. They experimented on a small single cylinder engine, having a cylinder diameter 10·5 in. and stroke 12 in. with a balanced slide valve controlled by a crank shaft governor, and for the purpose of the experiments the engine was made single-acting by the addition of a brass lap of sufficient length to the front end of the valve. A special cover was cast for the cylinder and fitted with eight thermo-couples

* *Proc. Inst. Civil Engs.*, Vol. CXV, 1893–94, Part I.
† *Trans. Amer. Inst. Elect. Engs.*, Vol. VIII, 1891.
‡ *Proc. Inst. Civil Engs.*, Vol. CXXXI, 1897–98, Part I.

at different depths. Any one or any two of these junctions could be connected to the galvanometer and to the cold junction by a suitable arrangement of mercury cups, and a contact maker could be set to close the galvanometer circuit at any point of the stroke and for any desired fraction of a revolution.

The electromotive force of the thermo-couple was balanced against that of a steady current flowing in a uniform potentiometer wire. In the first arrangement the external or " cold " junction was formed in a piece of cast iron, cast from the same ladle as the cylinder cover, and was maintained constantly at or very near 212° F. in a paraffin bath by means of a jacket of steam at atmospheric pressure. It was soon found that the cyclical fluctuations of temperature in the wall were so small that difficulty was experienced in getting consistent readings over any lengthy period of time because of the small incidental changes in the mean wall temperatures which nearly always occurred during the time required for complete observations on all the thermo-junctions. The thermoelectric circuit was then modified and consisted simply of the " hot " junctions as before, with the " cold " junction formed in the metal of the cover at a point having no cyclical variations of temperature, but having the same mean temperature as the " hot " junctions. By this means only the momentary small difference between the hot junction and the mean temperature of the metal was observed, for which the thermo-junction method is admirably suited. Nearly all the troubles that otherwise arose from the slow changes of temperature conditions were thus avoided, since a gradual change of temperature would affect the metal at a depth of $\frac{1}{2}$ in. practically to the same extent as at the surface of the metal.

The cylinder cover was provided with a steam-tight jacket as shown in Fig. 69. Eight holes for the junction wires, arranged in a circle of 1·5 in. radius round the centre of the cover, were bored to various depths, leaving from ·01 in. to ·64 in. thickness of metal measured from the inner surface. The thermo-couple wires were insulated with mica and india-rubber tube and washers, except at the bottom of the holes where they made contact with

the cast iron of the cover. In passing through the jacket they were protected by steel tubes screwed and soldered into the metal of the cover. A central tube was also provided in the cover for the clearance of a platinum-resistance thermometer carried by the piston to measure steam temperatures during the cycle. This thermometer is afterwards described on p. 133.

Commercially pure nickel was first tried against the cast

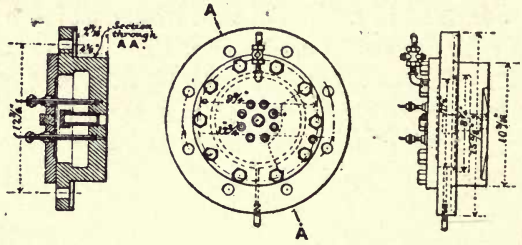


FIG. 69.—Callendar and Nicolson's arrangement of thermo-junctions in cylinder cover.

iron of the cover, but the electromotive force was found to be much less than with wrought-iron wire. All the iron wire used was from the same hank and carefully annealed after being bent into position. At first the iron wires were pressed against the bottom of the holes in the cover to form the junctions. Subsequently all the junctions were carefully soldered with pure tin to ensure complete and permanent thermal contact between the wires and the cover. Fig. 70 represents the arrangement of the thermo-junctions in the cylinder cover.

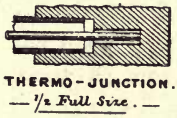


FIG. 70.

A set of eighteen thermo-junctions were also fitted along the side of the cylinder to observe the wall cycles and the distribution of temperature along the barrel surface.

The cycle contact-maker on the engine crank shaft closed the galvanometer circuit for any selected thermo-junction for a small fraction of a revolution at any desired point of the cycle. A pair of insulated revolving brushes were connected by a copper wire, and one brush made contact with a central

copper tube whilst the other made contact with a number of copper sectors of different lengths let into the circumference of a wooden disc. A galvanometer circuit could thus be closed by any of these sectors so as to alter the duration of contact. The point of the cycle at which the brush made contact was determined by the setting of a divided circle. The contact-

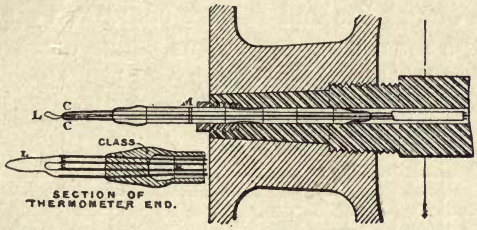


FIG. 71.—Platinum resistance thermometer in steam engine piston.

maker could be inserted in the circuit of either of two galvanometers, according as it was desired to observe a steam cycle with the platinum thermometer or a wall cycle with one of the thermo-couples.

The cylinder steam thermometers were platinum resistance thermometers made of very fine platinum wire ·001 in. in diameter. One was fixed in the central hole in the

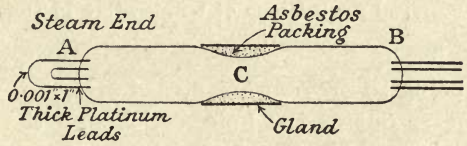


FIG. 72.—Construction of piston thermometer.

cylinder cover from which the first observations of steam temperatures were obtained. A comparison of the recorded steam temperatures throughout the whole cycle with the corresponding saturation temperatures deduced from the indicator diagram pressures showed that the steam in the hole in the cover was rather highly superheated throughout nearly the whole cycle. Another platinum resistance thermometer was then fixed in the piston as shown in Fig. 71, from which

it is seen that compensating leads were used as described on p. 27.

The construction of this thermometer is also illustrated in Fig. 72. There were the four leads of thick platinum wire fused into a glass tube at both ends A and B. In the middle of the tube a sort of constriction C was formed by melting in the glass so that it was very thick at that point. The leads which came out at the end B were connected on to the wires leading to the measuring apparatus. The constriction C was fitted into a gland with asbestos packing, the object of the

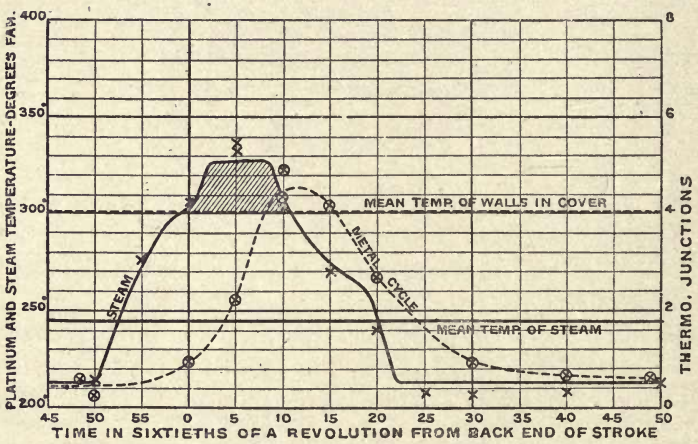


FIG. 73.—Cyclical fluctuations of temperature in steam engine cylinder.

constriction being to prevent the steam pressure from blowing the thermometer out of the hole. Although the portion AB was made of glass it was found that it would stand the steam being turned straight on to it, and although the measuring platinum wire was only ·001 in. diameter the wire was not broken by the rushing steam.

The diagrams in Fig. 73 show the character of the results obtained at a speed of 73·4 revolutions per minute. The full line was derived by the aid of steam tables from the pressures given by the indicator diagram. The points shown × are the temperatures given by the piston thermometer, from which it is seen that there is a fairly close agreement with the full line

diagram. The dotted line shows the cover wall temperatures at the depth of $\frac{1}{25}$ in. from the inner face, and it is seen that at this point the range of temperature is only about 4° F. An equation deduced in *Heat Transmission by Radiation, Conduction, and Convection*, may be used to estimate the probable range of temperature at the surface, and by this means the writer deduced a surface range of about 7° F.

Messrs. Coker and Scoble* have used similar methods to measure the fluctuations of temperature in the metal of the cylinder, in the inlet and exhaust valves, and in the piston of a small gas engine. The engine was of a standard pattern made by the National Gas Engine Company Ltd., and had a horizontal cylinder 7 in. diameter with stroke 15 in. It ran at a normal speed of 240 revolutions per minute, using town's gas. The thermo-junctions were composed of cast-iron plugs screwed into the metal of the cylinder, valves, and piston, with wrought-iron wires inserted in the plugs. The form of the couple or junction used is represented in Fig. 74 with reference to the inlet valve, which was bored out axially to allow the wrought-iron leads to pass to the hollow cast-iron plug inserted in the centre of the valve face. The inner diameter of the plug was about 5 mm. and the diameter of the wrought-iron wire 1 mm. The thickness of the metal at the face of the plug was about $\frac{2}{100}$ of an inch ; one wire was riveted through to the inner face and the other connected to the plug at a distance of about $\frac{1}{2}$ in. from the inner face. Any cyclical changes of temperature would be inappreciable at a depth of $\frac{1}{2}$ in. from the face, and thus only the cyclical variations of temperature at the surface of the plug were measured. In determining the mean temperatures of the metal the wire leading to the centre of the plug was used and the other not connected ; the circuit

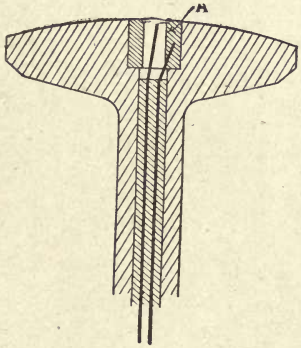


Fig. 74.—Thermo-junction in gas engine inlet valve.

* *Proc. Inst. Civil Engs.*, Vol. CXCVI, 1913–14, Part II.

was in this case completed at a convenient part of the engine frame.

The wires were insulated by two-way fire-clay tubes, and in all cases the cast-iron plugs were cut from the same bar and the wires taken from the same hank. The calibration of the couples was obtained by determining the potential difference between the hot and cold junctions when one was immersed in a solidifying metal and the other in melting ice. The calibrated values did not differ very much, and the following are given as an example :—

Hot junction, °C. = T	0	327	419	657
Electromotive force, microvolts = E .	15	3840	4500	6320

This corresponds very nearly with the formula :—

$$E \text{ (microvolts)} = -15 + 14T - \cdot 0068T^2.$$

Hence, $*\frac{dE}{dT} = 14 - \cdot 0136T.$

Five cast-iron plugs were inserted in the vertical diametral plane of the piston as is shown in the cross-section in Fig. 75. Only one wire was led from each piston couple, a long coiled spring supplying the flexible connection required by the motion of the piston. All the iron wires were riveted into the cast-iron plugs, as represented by the enlarged section of a couple in Fig. 75, the hole in the plug being about 3 mm. in diameter. There are some possible defects in the formation of these thermo-couples which are discussed later on p. 140.

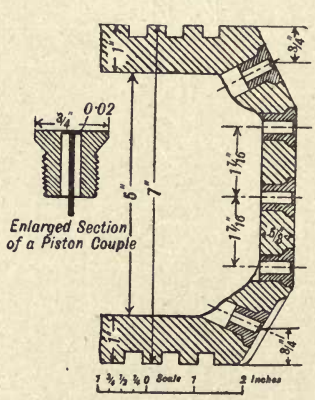


FIG. 75.—Arrangement of thermo-junctions in a gas engine piston.

The differences of potential were measured on the potentiometer or bridge principle described in Chapter III on p. 51. The

* Sometimes called the "thermoelectric power."

particular arrangement used by Messrs. Coker and Scoble is here illustrated diagrammatically in Fig. 76, where it is shown connected up to a thermo-couple H for the measure-

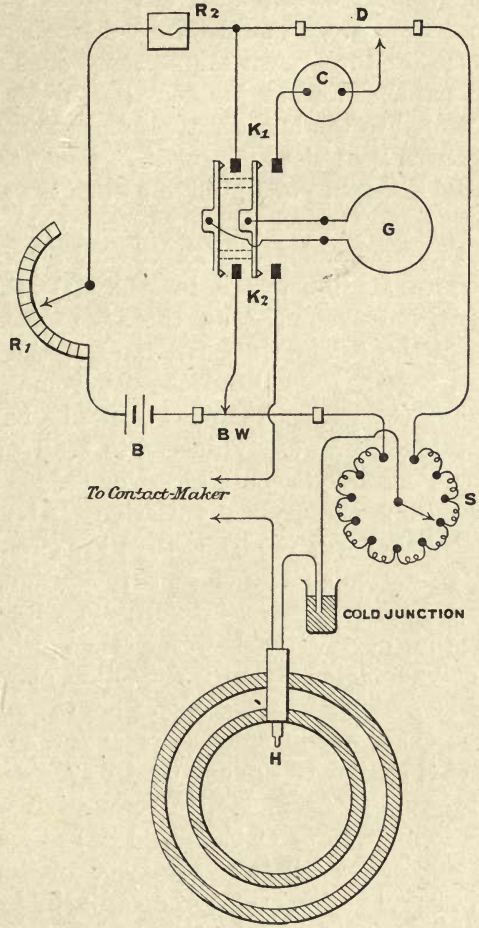


FIG. 76.—Potentiometer connections used in Coker and Scoble's experiments.

ment of gas temperatures, described in detail on p. 150. This potentiometer was used with all the couples by making the appropriate connections. The circuit containing the battery B was provided with the resistance R_1 and R_2, so that the fall of

potential between the extreme points of the bridge wire, BW, could be adjusted to 1 millivolt. This was tested by the electromotive force of the cadmium cell C, which could be opposed to the battery electromotive force on making contact with the upper key K_1. An adjustable contact D was used to make allowance for the known temperature coefficient of the standard cell used. The hot junction (H in the figure) had one lead connected to the lower key K_2 and the other to a set of step resistances S in the main circuit, each step of which gave a potential difference of 1 millivolt when the adjustments were correct. As explained previously the cold junction of some of the thermo-couples was formed at a point of mean wall temperature (as illustrated in Fig. 74) when cyclical variations were only required at these particular couples. The readings of the bridge wire, BW, and of the step resistance, S, taken together measured the electromotive force of the couple when the galvanometer G showed a balance. The scale of the bridge wire was graduated to read to 10 microvolts, and single microvolts could be estimated.

When determining the cyclical variations of temperature a rotary contact-maker was used, and then the circuit was only closed for a very small fraction of a revolution. For this reason a very sensitive galvanometer was necessary. The majority of the observations were taken when using a D'Arsonval galvanometer giving a deflection of 560 mm. for 1 microvolt on a scale distant 110 cms. from the mirror.

The contact-maker was ingeniously arranged, as represented in Fig. 77, and is similar to the one used by Messrs. Callendar and Dalby, referred to on p. 144, in connection with experiments on the temperatures of the gases in gas engines. The arrangement consists of a pair of insulated platinum-pointed springs, S_1S_2, carried on the arm A of an adjustable wrist-plate B. The latter is secured in a friction grip F concentric with the lay shaft of the engine. A pair of cams, C_1C_2, rotate with the lay shaft and allow the platinum point R_1 of one spring to make contact with a platinum face R_2 on the other spring for an interval depending on the angular distance between the two steps, T_1T_2,—usually about 6° in Messrs. Coker and Scoble's experiments. For a complete cycle of readings the

wrist-plate can be set in successive positions for the springs to make contact as the lay shaft revolves. As the readings for a complete cycle take some little time to obtain, every precaution has to be taken in such experiments to keep the running conditions of the engine as constant as possible.

The results of Messrs. Coker and Scoble's experiments may be briefly summarised as follows : The mean temperature of the cylinder liner was not more than 40° C. (72° F.) above the

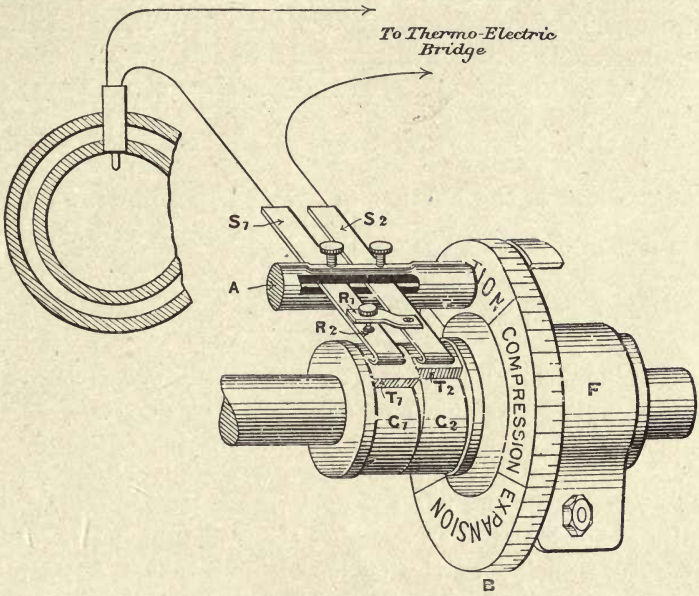


FIG. 77.—Adjustable contact-maker for thermo-junctions.

temperature of the jacket water at outlet. The surface of the combustion chamber may rise in places to as much as 250° C. (482° F.) with a cyclical change of about 20° C. (36° F.) as measured at the position E in Fig. 55, p. 111. The maximum temperature of the inlet valve was in the neighbourhood of 310° C. (590° F.) and had a cyclical change at the surface of 10° C. to 20° C. ; at the exhaust valve the corresponding temperature was 400° C. (752° F.) with a cyclical change of 10° C. to 15° C.

The piston of 7 in. diameter had a low maximum tempera-

ture of about 340° C. (644° F.), with the considerable cyclical change at the centre of about 80° C. (144° F.) as a maximum value, and with a somewhat smaller range near the top and bottom.

It is now proposed to discuss some of these results at some length with a view to showing that the arrangement of the thermo-junction may be somewhat defective. If it be taken that the average range of surface temperature at the piston was about 74° C. and that of the surface of the combustion chamber 20° C., and assuming, for simplicity of calculation, simple harmonic changes of temperature at the wall surface,* the flow of heat into and out from the surface of the metal per cycle would be $\frac{4a}{\sqrt{N}}$ per square foot of surface,† where a is half the range and N the number of cycles per minute. At 120 cycles per minute this becomes $\frac{4 \times 74 \times \cdot 267}{2 \times 11} = 3 \cdot 59$ heat units per cycle at the piston, and $\frac{4 \times 20}{2 \times 11} = 3 \cdot 64$ units for the combustion chamber, altogether 7·23 heat units per cycle. The area of the piston was ·267 of a square foot and that of the combustion chamber about 1 square foot. According to the values given in the paper there were only about 8 heat units available in the gas per cycle, and yet something like 7 units are calculated as entering the walls during the high temperature period of the cycle, without taking account of any heat flowing directly to the jacket. In any case, even neglecting the results of these approximate calculations, the amount of heat entering each square foot of the walls per cycle is likely to be proportional to the fluctuation of temperature, that is for the piston $\frac{74}{12} = 6 \cdot 2$ times the rate at which the exhaust valve received heat according to the range of temperatures given. There does not appear to be

* Although the measured surface temperatures plotted on a crank angle base differed somewhat from a simple harmonic curve the approximation is sufficiently near for the purpose in view.

† Refer to *Heat Transmission by Radiation, Conduction, and Convection* for proof.

any evident reason for this, and it is to be inferred that the methods employed were faulty.

An examination of the dimensions and arrangement of the thermo-couples in Figs. 74 and 75 shows that the metal in the neighbourhood of the couple did not really imitate the actual conditions in the body of the metal of the valves, combustion chamber and piston. Neglecting for the moment the presence of the comparatively thin wrought-iron wire of the couple, and assuming that the heat flow per cycle into and out of the body of the metal through the surface was about $\frac{4a}{\sqrt{N}} = \cdot 364a$ heat units per square foot, it is deduced by a similar calculation in *Heat Transmission by Radiation, etc.* that the amount of heat passing through the body of the metal wall at ·02 in. depth in the same period is of the order $\cdot 24a$. But with the thermo-couples, where the disc of metal was only ·02 in. thick, nearly all the heat entering the surface had to be stored in this thin disc. Taking the rise of temperature to be proportional to the heat stored, then,

$$\frac{\text{Heat stored in ·02 inch thick in wall}}{\text{,, ,, ,, ·02 ,, ,, at couple}} = \frac{\text{Actual range of wall.}}{\text{Range of thermo-couple wall.}}$$

$$= \frac{\cdot 364 - \cdot 24}{\cdot 364}$$

$$= \tfrac{1}{3} \text{ nearly.}$$

This result indicates that the range of temperature at the piston as measured was possibly about three times too large when compared with the conditions at the normal thickness of metal.

If the actual cyclical changes of temperature were considered instead of assuming simple harmonic fluctuations, and the conduction of the thin wrought-iron wire forming part of the thermo-couple were taken into account, the above conclusion might be modified somewhat, but the defect as it stands can be largely obviated by using a wire of larger relative diameter, as was done by Messrs. Callendar and Nicolson in Fig. 70, p. 132.

The same arguments might be applied against the results obtained in the combustion chamber wall and in the valves, but in these cases it would be noticed that the cyclical changes

of temperature were measured above and below the mean. Now there is always the possibility of localised disturbing or parasitic currents being set up by the insertion of a cast-iron plug in another metal of different composition or nature, with the result that such parasitic currents may affect the reading to some unknown extent when only small differences are being measured. In any case, it is obvious that with such couples an examination and a test should be made to ascertain whether the presence of the plug affects the normal conditions to any appreciable extent.

Gas Temperatures in a Gas Engine Cylinder.—Various attempts have been made to measure the temperature of the gases in a gas engine cylinder at different points in the cycle both by means of platinum resistance thermometers and by

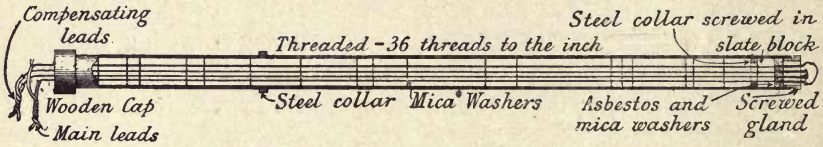


FIG. 78.—Professor Burstall's platinum resistance thermometer for measuring gas temperatures in a gas engine.

thermo-junctions. The greatest difficulty has been experienced in keeping the platinum wires intact for the reasons that the highest temperature after a normal explosion is generally beyond the melting point of platinum, and thin wires are liable to breakage on account of the intense convection currents in the gases. By using relatively thick platinum wires, ·0015 to ·0025 in. diameter, Professor Burstall* found that it was possible to preserve the platinum wire against fusion in a small gas engine using coal gas, provided only weak charges were used with about one explosion in six cycles, but no doubt this was only in consequence of the appreciable lag of temperature involved by the use of such thick wires. Attempts made with platinum wires ·001 in. diameter failed because the wire always fused after a very few explosions. The construction of the platinum resistance thermometer used by Professor

* "Second Report to the Gas-Engine Research Committee," *Proc. Inst. Mech. Engs.*, 1901, p. 1031.

Burstall is shown in Fig. 78. It consisted of a solid drawn steel tube about 1 in. diameter and 18 in. length, having a thickness of about $\frac{1}{20}$ of an inch. The outside of the tube was threaded from end to end and had upon it a pair of nuts to allow the measuring wire to be placed at any distance from the wall of the cylinder. The nuts also served to hold the thermometer in position by means of an ordinary screwed gland packed with asbestos. The inside of the right-hand end of the tube in the figure was bored out for a short distance and internally threaded. A circular slate block fitted into the bored-out portion of the tube. The four leads, which were of platinum, passed through the holes in the slate block, and to prevent the leads being blown out of the tube by the pressure each lead was provided with a small platinum collar which was allowed to bear against the outside of the slate block. The whole was made gas-tight by means of alternate layers of asbestos and mica, which were forced down by means of a gland. The leads were insulated from each other by mica washers at short intervals. Moisture, by wetting the asbestos, destroys such insulation, and therefore in finding the resistance of the platinum loop in ice and steam the thermometer was protected from direct contact with moisture by a thin copper tube. The length of the loop of measuring wire was about $\frac{3}{4}$ in., the compensation leads being joined by a small length of about $\frac{1}{4}$ in.

A wipe contact-maker was used consisting of a wooden disc attached to the lay shaft and having a small block of brass let into its circumference. Two copper springs made contact with this block, once in each cycle, and this could be adjusted to the various points of the cycle ; thus the galvanometer circuit was completed when the brass block and the copper springs made contact. In addition to this, however, the galvanometer circuit had a relay contact arranged to close this circuit by the movement of the gas admission valve, so that readings only were obtained on explosion cycles, and this relay contact was broken by a contact on the exhaust valve on the engine. As the temperatures varied slightly from cycle to cycle it was impossible to get an accurate balance of the resistances by the methods explained on p. 27, so the

method employed was to put such a resistance into the resistance box that the galvanometer would throw constantly to one side. Ten readings were made of the galvanometer throws and then a second resistance was put in of such magnitude that the galvanometer throws were all on the opposite side from that of the previous determination. Ten throws were again observed and the resistance interpolated from the mean of these twenty readings.

Experiments were made with the measuring wire at various depths in the cylinder ; first in a small cavity on a level with the inner wall, then when standing out about $\frac{1}{2}$ in., and also with the measuring wire bent back as near as possible to the steel body of the thermometer. The temperatures thus obtained showed a decided falling off as the wire was brought close up to the wall, amounting in one case to nearly 200° C.

Professors Callendar and Dalby* have experimented on the measurement of gas temperatures on a small gas engine. They used a platinum resistance wire of ·001 in. diameter and found that the lag of temperature with such a fine wire was quite small, but they attached this thermometer to a special valve T arranged as shown in Fig. 79 in the centre of the admission valve A and operated by a special cam on the side shaft. In this figure the valve T is shown open to the fullest extent, and it is seen that the spindle near the head was formed of two ribs, RR, made as thin as possible so as to leave the contained platinum wire freely exposed to the gases when the valve was open. It was arranged that the thermometer valve T should only be open during the suction and compression strokes and remain on its seat on the valve A during the high temperature period of the cycle. By this means the gases at high temperatures were kept out of contact with the platinum wire. A special contact-maker was employed similar to that illustrated in Fig. 77 on p. 139 so as to obtain the temperature of the gas at any point of the cycle when the thermometer valve was open.

The average temperatures of the gases during expansion were calculated by means of the gas formula $\frac{PV}{\tau} = \text{constant}$,

* *Proc. Roy. Soc.*, Vol. LXXX, 1908, p. 57.

allowing for the shrinkage of volume due to chemical combination, and also assuming the combustion to be complete and no valve or piston leakage. This involved the accurate measurement of the absolute pressure P and volume V at all points in the cycle. For this purpose the manograph type of optical indicator was used having a pressure diaphragm operating a tilting mirror, by which means a beam of light was thrown on to a sensitized plate and gave a record of pressures at all points in the cycle. The reason for using such an indicator is the lack

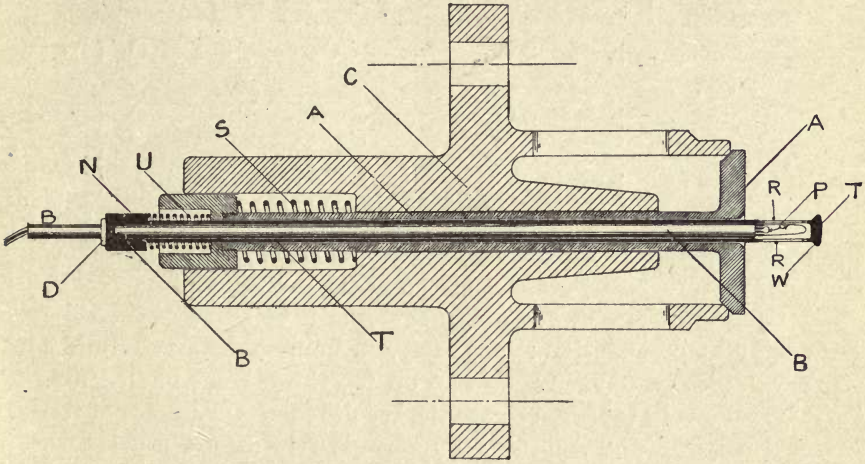


FIG. 79.—Thermometer valve in the admission valve of a gas engine.

of accuracy of ordinary piston and pencil indicators due to the inertia and the frictional resistance of the moving parts.

Shrinkage of Volume due to Combustion.—It was mentioned just previously that, before the absolute temperatures τ could be calculated for the gas during the expansion period of the cycle, an allowance must be made for the shrinkage of volume of the gases due to the chemical combination. As an example of the method of calculation consider the results obtained from coal gas of the following composition.

Constituents of coal gas.	Per cent. by volume.
Methane or marsh gas (CH_4)	33·73
Unsaturated hydrocarbons assumed (C_2H_4) .	4·74
Hydrogen (H_2)	41·29
Carbon monoxide (CO).	7·13
Nitrogen (N_2).	10·22
Carbon dioxide (CO_2)	2·62
Oxygen (O_2)	0·27

The first four constituent gases in the above sample are the combustibles. The chemical symbols expressing the complete combustion process in oxygen are as follows :—

1 molecule marsh gas	+	2 molecules oxygen	=	1 molecule carbon dioxide	+	2 molecules water-vapour	
CH_4	+	$2\,O_2$	=	CO_2	+	$2\,H_2O$	(*a*)

Similarly,

C_2H_4	+	$3\,O_2$	=	$2\,CO_2$	+	$2\,H_2O$	(*b*)
$2\,H_2$	+	O_2	=	$2\,H_2O$			(*c*)
$2\,CO$	+	O_2	=	$2\,CO_2$			(*d*)

Chemical theory asserts that the volume occupied by one molecule of an elementary or a compound gas at any particular temperature and pressure is the same for all gases. Hence 1 volume of marsh gas (CH_4) requires 2 volumes oxygen for complete combustion ; similarly, 1 volume (C_2H_4) requires 3 volumes of oxygen ; and so on for the other constituents. The following table expresses the results for 100 volumes of the coal gas, where all volumes are referred to the same temperature and pressure conditions. Thus, as 1 volume of CH_4 produces 1 volume of CO_2 and 2 volumes of H_2O, then 33·73 volumes CO_2 and 67·46 volumes H_2O are respectively produced by 33·73 volumes CH_4, and so on for the other combustible gases.

Chemical symbol.	Volumes of gas.	Volume of oxygen required.	Volume of carbon dioxide produced.	Volume of steam produced.	Total volume of products of combustion.
CH_4 .	33·73	$2 \times 33{\cdot}73 = 67{\cdot}46$	33·73	67·46	101·19
C_2H_4 .	4·74	$3 \times 4{\cdot}74 = 14{\cdot}22$	9·48	9·48	18·96
H_2 . .	41·29	$\frac{1}{2} \times 41{\cdot}29 = 20{\cdot}64$	—	41·29	41·29
CO . .	7·13	$\frac{1}{2} \times 7{\cdot}13 = 3{\cdot}57$	7·13	—	7·13
N_2 . .	10·22	—	—	—	10·22 (from air = 397·4)
CO_2 .	2·62	—	2·62	—	2·62
O_2 . .	0·27	0·27 deducted	—	—	—
Gas .	100·0	105·62	52·96	118·23	181·41
					+397·4
					578·81

Since air to oxygen in atmosphere is in the ratio 100 to 21 nearly,

$$\left.\begin{array}{l}\text{Volume of air required for complete}\\ \text{combustion of 100 volumes gas}\end{array}\right\} = \tfrac{100}{21} \times 105{\cdot}62$$

$$= 503 \text{ volumes}$$

$$\text{Volume of nitrogen taken in with air} = \frac{79}{21} \times 105{\cdot}62$$

$$= 397{\cdot}4 \text{ volumes.}$$

Hence 1 cub. ft. of gas requires 5·03 cub. ft. of dry air, and produces 5·788 cub. ft. after combustion, assuming that the steam remains a vapour ; but if the steam is condensed, the volume of products becomes $(5{\cdot}788 - 1{\cdot}182) = 4{\cdot}606$ cub. ft. Suppose that y cub. ft. of air are supplied in excess per cub. ft. of gas, then,

$$\left.\begin{array}{l}\text{Total dry air supplied per}\\ \text{cub. ft. gas}\end{array}\right\} = (y + 5{\cdot}03) \text{ cub. ft.}$$

On the assumption that the steam remains a vapour and that the combustion is complete, then,

$$\frac{\text{Volume of air left in actual products of combustion}}{\text{Total volume of actual products of combustion}} = \frac{y}{y + 5{\cdot}788}$$

Now, when a sample of exhaust gas is analysed the water-vapour formed by combustion has become condensed, with a corresponding shrinkage in volume ; therefore, if the steam produced by combustion is condensed,

$$\frac{\text{Volume of air left in products of combustion}}{\text{Total volume of products of combustion}} = \frac{y}{y + (5{\cdot}788 - 1{\cdot}182)}$$

$$= \frac{y}{y + 4{\cdot}606}$$

If the exhaust gas analysis was known, and it was found to contain O% oxygen by volume, then,

$$\left.\begin{array}{l}\text{Excess volume of air in 100 volumes}\\ \text{exhaust gases, equivalent to O}\\ \text{volumes of oxygen}\end{array}\right\} = \text{O} \times \tfrac{100}{21} \text{ volumes air,}$$

therefore,

$$\frac{y}{y + 4{\cdot}606} = \frac{\text{O} \times \frac{100}{21}}{100}$$

or,

$$y = \frac{4{\cdot}606\text{O}}{(21 - \text{O})} \text{ cub. ft. per cubic foot of gas.}$$

EXAMPLE.—With the above sample of town gas the exhaust gas analysis in one test gave 11% by volume oxygen. Calculate volume of air supplied per cub. ft. of gas.

$$y = \frac{4{\cdot}606 \times 11}{21 - 11} = 5{\cdot}07 \text{ cub. ft.}$$

$$\left.\begin{array}{l}\text{Total dry air supply} \\ \text{per cub. ft. gas}\end{array}\right\} = 5{\cdot}03 + 5{\cdot}07 = 10{\cdot}1 \text{ cub. ft.}$$

Volume of mixture before combustion $= 1 + 10{\cdot}1 = 11{\cdot}1$ cub. ft.

$$\left.\begin{array}{l}\text{,,} \quad \text{,,} \quad \text{after} \quad \text{,,} \\ \text{(water vapour not condensed)}\end{array}\right\} = y + 5{\cdot}788$$

$$= 5{\cdot}07 + 5{\cdot}788$$

$$= 10{\cdot}86 \text{ cub. ft.}$$

$\therefore$ Shrinkage due to combustion $= \dfrac{11{\cdot}1 - 10{\cdot}86}{11{\cdot}1} \times 100 = 2{\cdot}2$ per cent.

Thus in this case, if P_1, V_1 and τ_1 represent the absolute pressure, absolute volume and absolute temperature respectively at a particular point during compression, and P_2, V_2 and τ_2 represent the corresponding values at any particular point on the subsequent expansion stroke, then,

$$\frac{P_1 V_1}{\tau_1} = \frac{P_2}{\tau_2} V_2 \left(\frac{100}{100 - 2{\cdot}2} \right)$$

Since all the values are known except τ_2, then,

$$\tau_2 = \frac{P_2}{P_1} \times \frac{V_2}{V_1} \times \tau_1 \times 1{\cdot}022$$

In the above calculation it is assumed that the combustion is complete and that there is no appreciable leakage of gases from the cylinder between the points considered. Therefore, care has to be taken to have the valves and piston rings in good condition during the experiments.

It is to be noted, however, that the calculated temperatures are only averages for the gases at any particular instant during expansion. The late Professor Hopkinson* made some experiments with a large cylindrical explosion vessel of capacity 6·2 cub. ft., in which he measured the temperature of the gases at different points in the vessel after explosion, also measuring the

* *Royal Soc.*, 1906.

pressure by means of an optical indicator. Each thermometer consisted of a coil of about 5 cm. of pure platinum wire ·001 in. diameter. The leads were of copper carried in glass tubes to protect them from the action of the flame. Each thermometer coil was placed in series with a storage cell and with a D'Arsonval galvanometer having a comparatively stiff phosphor-bronze suspension. The period of oscillation was thus made from $\frac{1}{50}$ to $\frac{1}{30}$ of a second, with the result that the oscillations were sufficiently rapid and small as to cause little trouble in getting a mean reading of the variation of current in the platinum coil due to alteration of resistance with temperature. The mirror of the galvanometer was arranged to throw the image of a fine hole, illuminated by an arc lamp, on a revolving drum carrying a photographic film. The record of pressures was also taken on the same drum.

It was always found that the temperature near the point of ignition (at centre of vessel) at the moment of maximum pressure was always higher than at other places in the vessel. With a mixture of 1 volume of coal gas to 9 volumes of air ignited at atmospheric pressure, Professor Hopkinson estimated the following distribution of temperatures at the point of maximum pressure when the gas was ignited at the centre of the vessel.

Time to attain maximum pressure after ignition, about	·25 sec.
Temperature at centre of vessel	1900° C.
,, ,, 4 in. from wall	1700° C.
,, ,, ·4 in. from wall at end .	1100 to 1300° C.
,, ,, ·4 in. from wall at side . . .	850° C.
Mean temperature (estimated from pressure) . .	1600° C.

The main reason for these differences is the different conditions under which the gas is burned at the different points in the vessel. Near the point of ignition the gas is burned at nearly the initial pressure and acquires a temperature dependent upon the amount of heat generated and the specific heat of the gas at constant pressure. As the pressure rises the gas at the centre is compressed nearly adiabatically, which results in a corresponding rise of temperature to a value higher

than at any other point in the vessel. Near the walls, i.e. remote from the point of ignition, the gas is compressed by the wave of pressure before the flame reaches it, and the resultant temperature is not so high as near the point of ignition.

Within half a second after maximum pressure convection has had time to take effect and the distribution of temperature is much more uniform as is shown by the following values.

Time from ignition	·75 sec.
Temperature at centre of vessel . . .	1100 to 1200° C.
Mean temperature determined by a long platinum wire from centre to near the wall (excluding layer of gas 1 cm. thick near wall)	1160° C.
Mean temperature (estimated from pressure) . .	1100° C.

In a gas engine cylinder, however, convection is much more intense than in a gas vessel of constant volume used in the manner described, for the reason that the gases are in very rapid motion both just before and after entering a gas engine cylinder, and it is well known that the rapidity of combustion is much greater in a gas engine cylinder than in a gas vessel of constant volume, due to these intense convection currents. A moment's consideration would suggest that this must be so since there is no great difficulty in igniting and burning a fairly rich combustible mixture in an engine running at 2000 revolutions per minute or over, i.e. something like 17 complete cycles per second.

In the course of the experiments described on pp. 135 to 142, Messrs. Coker and Scoble made a fairly successful attempt to measure directly the cyclical temperatures of the gases at the position E in Fig. 55, near the top of the combustion chamber. They used a thermo-junction made of two wires, one wire being an alloy of platinum and rhodium 10%, and the other an alloy of platinum and iridium 10%, both wires being obtained from Messrs. Johnson, Matthey and Company. It was found that these alloys were able to withstand the temperature of the explosion under normal conditions with an explosion every cycle when the thin wires were

flattened to a thickness of $\frac{5}{10,000}$ to $\frac{8}{10,000}$ of an inch. The couple was arranged as shown in Fig. 80, where the steel sheath D was pressed against a seating at V in the special casting at the top of the combustion chamber. A two-way fire-clay tube A containing the couple was secured in the sheath with plaster of Paris. The inner ends of the wires were rolled out to the required thickness and fused together electrically, and afterwards the junction was finally rolled out to the thickness mentioned above. The strip so formed was trimmed down to approximately the contour of two truncated triangles with the central junction at the narrowest part. This form was adopted to provide a loop strong enough to hang in a vertical position in spite of the violence of the explosions, and it was therefore set with the planes of its flat faces parallel to the axis of the engine cylinder to offer the smallest obstruction,

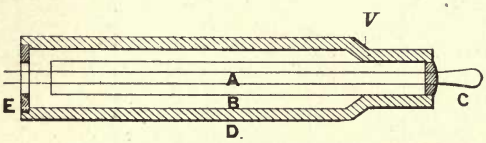


FIG. 80.—Coker and Scoble's thermo-junction for gas temperatures in a gas engine.

and was arranged to project about $\frac{1}{2}$ in. into the cylinder. When examined through a magnifying glass the edges of the wires sometimes showed signs of fusion and consequent thickening after long exposure. With an abnormal explosion the wires were generally fused at the junction.

In order to test the delicacy of the indications of these couples at low temperatures a number of experiments were made with the exhaust valve locked and the engine motored round, and a very fair agreement was obtained between the temperatures calculated from the compression and expansion of the trapped air and those observed with the thermo-couples. The electromotive force obtained at the highest temperatures of explosion varied between 7 and 8 millivolts. Calibrations were checked by Dr. Harker at the National Physical Laboratory up to 1283° C. (2341° F.), as shown in the following table.

Temperature, °C. =T	0	490	840	1003	1283
Electromotive force, microvolts = E	0	3152	5036	5773	6382

These results corresponded well with the formula :

$$E = -174 + 7{\cdot}6075T - {\cdot}001673T^2,$$

and this expression was used to determine the temperatures

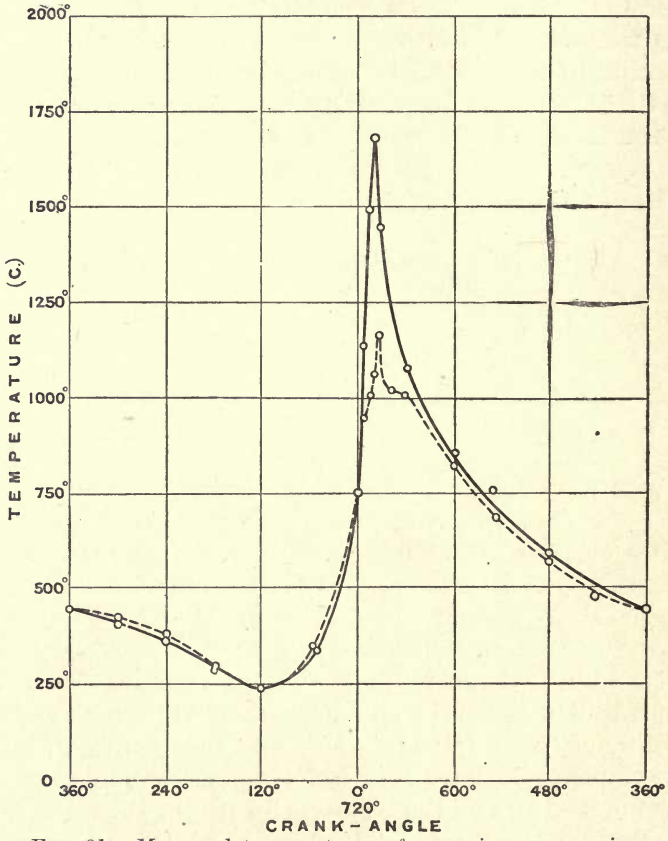


FIG. 81.—Measured temperatures of gases in a gas engine.

obtained in the trials on the assumption that it held for extrapolated values beyond the range of calibration.

Two of the determinations of the temperature cycle of the

gas charge are shown in Fig. 81. The maximum temperature here recorded is 1675° C., which, allowing for the cold junction correction to 0° C., gave a maximum temperature of 1705° C. In this case a further estimate of the highest temperature was obtained, for it was found that the electromotive force of the couple suddenly became lower at the explosion point, although at other points it remained much the same as shown by the dotted curve. On taking out the couple it was found that this was due to the junction fusing without breaking. Some recent experiments made by Dr. Harker at the National Physical Laboratory on these 10% alloys show that they both melt at a temperature about 100° C. higher than the melting point of platinum, that is, at about 1850° C., and therefore this temperature must have been attained by the fused couple.

Some further experiments were made with the addition of an optical indicator to measure the highest pressures obtained during the explosion. The pressures, volumes, and temperatures were measured at points on the compression and expansion curves to obtain the value of the gas constant, $\frac{PV}{\tau}$, and from this to calculate the temperature corresponding to the maximum pressure. The following are representative values obtained, and for the calculation of the maximum temperature the constant was selected at 21·45.

COMPRESSION.

Absolute pressure, lbs. per sq. in.	Volume cub. in.	Recorded temperature absolute, °C.	$\frac{PV}{\tau}$	True temperature absolute, °C. (using $\frac{PV}{\tau}$ = 21·45)	True temperature, °C.
108·0	130·4	641	22·0	—	—
81·3	165·0	603	22·2	—	—
57·1	220·0	570	22·0	—	—
41·3	283·0	546	21·4	—	—

EXPANSION.

84·5	358·0	1376	22·0	1410	1137
63·1	439·0	1328	20·9	1292	1019
53·7	516·0	1295	21·4	1291	1018
45·9	576·0	1261	21·0	1234	961
353·0	130·4	—	—	2144	1871

There is always some uncertainty with these couples since platinum-iridium alloy changes with prolonged heating at high temperatures, with a consequent influence on the electromotive force. Considering this influence, the experimenters concluded that the change of electromotive force during an

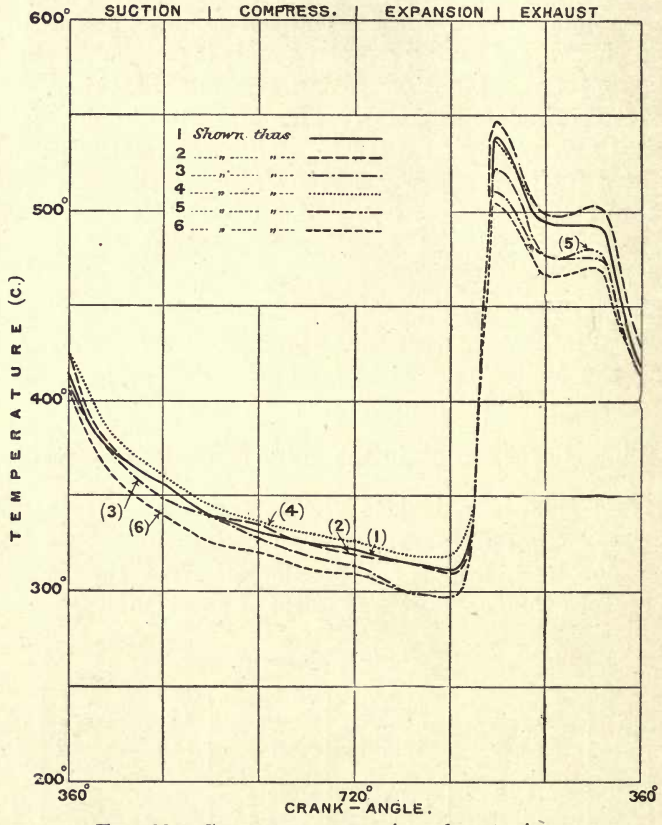


FIG. 82.—Gas temperatures in exhaust pipe.

ordinary trial would be less than $2\frac{1}{2}\%$. There is also some little danger of the wires becoming contaminated with absorbed carbon from the gases at high temperatures.

A thermo-couple was inserted in the centre of the exhaust pipe as near to the cylinder outlet as possible. The couple was pure platinum and a 10% alloy of iridium-platinum. Fig. 82

illustrates the character of the results obtained with various strengths of gas mixtures and different jacket temperatures, an explosion occurring every cycle. The result of all the variations in the conditions of running of this engine was to produce a difference of about 40° C. in the maximum temperature of the gases in the exhaust pipe, which is always between 500° C. (932° F.) and 550° C. (1022° F.).

In all these experiments no account appears to have been taken of the radiation from the surface of the wires forming the thermo-couple in the combustion chamber. It is generally accepted that, within limits, the total radiation from platinum is proportional to the fifth power of the absolute temperature. Thus at high temperatures the thermo-couple would be a fairly effective radiator to the comparatively cold walls of the combustion chamber. Probably the presence of the surrounding gases would interfere very little with the rate of heat loss by radiation, and the writer would suggest that, due to radiation, there is the possibility of appreciable errors in the measurement of the gas temperature during the high temperature period of the cycle. In other words, when the wire is losing heat by radiation its temperature tends to fall, and at any instant its temperature would be as much below that of the gas as would be required for the heat lost by radiation to be made up by heat received by radiation and by contact with the gases.

To illustrate this particular point Professor Callendar has made experiments* on two platinum wires as resistance thermometers, one being $\frac{6}{1000}$ of an inch diameter and the other $\frac{4}{1000}$ of an inch, first placed together in a porcelain tube and connected differentially with a recording instrument. When the two wires were heated together in the porcelain tube the indication of the apparatus did not vary, showing that they were at the same temperature ; but when directly exposed to the flame, the finer wire became about 60° C. hotter than the other. Dr. F. Haber† estimates that a thermo-junction with wires about ·1 mm. (·004 in.) diameter and exposed to a Bunsen flame has a temperature more than 30° C.

* Discussion on "Second Report to the Gas-Engine Research Committee," *Proc. Inst. Mech. Engs.*, 1901, p. 1111.

† *Thermodynamics of Technical Gas Reactions*, p. 298.

below the true temperature of the flame. Other examples are given in *Heat Transmission by Radiation, Conduction, and Convection*, in connection with the measurement of flue gas temperatures in a boiler.

Although the influence of radiation from a round wire as small as ·001 in. diameter is likely to be almost negligible, the wires of the thermo-junction used by Messrs. Coker and Scoble were flattened and thus probably had a relatively large radiating surface. The influence of this cannot be estimated without further experiments.

TABLES AND DATA

TABLE I

BOILING POINTS OF WATER FOR THERMOMETER CALIBRATIONS

(MARKS AND DAVIS' STEAM TABLES)

Press. in. of mercury.	Temperature °F.	Press. in. of mercury.	Temperature °F.
28·0	208·67	30·2	212·47
·2	209·03	·4	212·81
·4	209·37	·6	213·13
·6	209·73	·8	213·46
·8	210·08	31·0	213·80
29·0	210·42	·2	214·13
·2	210·76	·4	214·46
·4	211·10	·6	214·79
·6	211·44	·8	215·11
·8	211·79	32·0	215·43
30·0	212·13	—	—

TABLE II

STANDARD BOILING POINTS FOR THERMOMETER CALIBRATIONS

Substance.	Boiling point at 29·92 in. of mercury °F.	Variation with pressure near atmospheric pressure, inches mercury per deg. Fahr.
Aniline . . .	363	·429
Benzophenone .	583	·346
Naphthalene . .	424·5	·374
Sulphur . . .	832·5	·241

TABLE III

MELTING OR SOLIDIFYING POINTS FOR PYROMETER CALIBRATIONS

Metal or salt.	Melting Point.	
	°F.	°C.
Aluminium	1216	658
Cadmium	610	321
Copper	1983	1084
Gold	1947	1062
Iron	2772 ± 27	1522 ± 15
Lead	621	327
Nickel	2642 ± 18	1450 ± 10
Mercury	− 38	− 38·9
Palladium	2815	1546
Platinum	3190	1754
Silver	1762	961
Tin	449	232
Zinc	787	419
Sodium Chloride	1472	800
Sodium Sulphate	1625	885

TABLE IV

RELATIVE EMISSIVITY E AT HIGH TEMPERATURES

Metal.	Value of E for Wave Length.*		E for Total Radiations.
Iron (polished)	·28	for ·66 μ.	·29
Iron (molten)	·29 at 2400° F. to ·46 at 3000° F.	,, ·66 μ.	·28
Iron (oxide)	·94 at 1800° F.	, ·65 μ.	·87
Copper	·11	,, ·66 μ.	—
Copper (molten)	·13	,, ·65 μ.	·15
Cuprous oxide	·8 at 1800° F. to ·5 at 2200° F.	,, ·65 μ.	·60
Nickel (solid)	·25	,, ·66 μ.	—
Nickel oxide	—	—	·62 at 1300° F. to ·88 at 2460° F.
Platinum	—	—	·14 at 2100° F. to ·18 at 3100° F.
Gold	·114 at 1800° F.	,, ·67 μ.	—
Silver	·05	,, ·66 μ.	—

* μ here represents the length $\frac{1}{1000}$ mm.

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